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AN ANALYSIS OF THE RELATION OF PRECIPITATION TO TOPOGRAPHY IN THE INTERPROVINCIAL BOUNDARY REGIONS OF ALBERTA AND BRITISH COLUMBIA.

by

© LEE, YEAN

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "An Analysis of the Relation of Precipitation to Topography in the Interprovincial Boundary Regions of Alberta and British Columbia", submitted by Lee Yean in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Regression techniques were used in a first attempt to establish simple relationships between elevation, slope, and precipitation for 28 stations in Alberta and 31 station in British Columbia, located in the vicinity of the Continental Divide. It was soon found that no simple relationships exist among these quantities when all the stations, of wide diversity in location, elevation, exposure etc. are analysed together, lumped in two groups, east and west of the Continental Divide, respectively. However, quasi-linear relationships may be established for small groups of stations in closely similar locations, e.g. in the same valley, and on the same slope of a mountain range. Using these "local" relationships as points of departure, it was possible to derive similar relationships for the neighbouring slopes and ridges. Judicious extrapolation and use of all observational material led in turn to a stepwise first-approximation solution of the precipitation distribution in the study area. To facilitate realistic analysis and extrapolation, the study area was subdivided into five zones, based on meteorological and physiographic criteria.

This study made use of two "key" reference regions, the Old Glory Mountain region, and precipitation zone IV.[*] Within zones I, II and III adequate estimates could be derived from observed data, but estimated precipitation amounts for fictitious stations had to be used as data for zone IV and zone V.

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[*] See page 48 for map of precipitation zones.

On the basis of the quasi-linear relationship, a set of first approximation isohyetal maps and two precipitation profiles were drawn up for the study area.

Harmonic analysis was used with a view to identifying likely physical causes for the precipitation maxima and minima in the mountainous area; only a few tentative conclusions could be reached at this time.

The simple model developed for estimating precipitation amounts on the peaks of mountains was tested by comparing predicted values with the precipitation recorded at a number of forestry lookout stations located on the eastern slopes of the Rockies. The results of this test seem to suggest that the model is capable of providing good estimates of precipitation amount for the seven to eight thousand feet levels of the Rockies east of the Continental Divide.

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INTRODUCTION

The determination of precipitation distribution in mountainous regions, one of the central problems of mountain hydrometeorology, has attracted the attention of hydrologists and meteorologists for many years. The literature on this subject is extensive and growing, with contributions from all disciplines concerned with the effective utilization and control of water resources, but the basic problem remains largely unsolved. Much of the early work was of an observational and descriptive nature, and most of the solutions were piecemeal and empirical. Gradually, however, more and more quantitative methods of estimation and forecasting have been introduced. Recently, American investigators have successfully applied various correlation techniques and dynamical methods to the problem[1].

Very little work has been done so far on the precipitation distribution in the mountainous areas of Alberta and British Columbia. The main reason for this apparent neglect seems to be thinly-spaced network of precipitation gauges. The lack of gauges is especially acute on the ridges and upper slopes of the mountains, and in the remoter parts of both provinces. The recent loss by fire of the Old Glory Mountain Observatory, the only first order high level station

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[1] J.I. Burns, "Small-Scale Topographic Effects on Precipitation in San-Diams Experimental Forest". Trans. Amer. Geophys. Union, Vol. 34(5), 1953, pp. 761-768.

V.A. Myers, "Airflow on the Windward Side of a Large Ridge". J. Geophys. Res., Vol. 67, No. 11, 1962, pp. 4267-4291.

(7,700 feet) in Canada, is thus doubly regrettable and severe.

Muttitt states "Alberta lies to the east of, and in the shelter of the mighty Rocky Mountains. It is, as Kendrew has stated, in the rain shadow of the Rockies"[2]. A survey of the average monthly precipitation for 28 stations in Alberta and 31 stations in British Columbia in or in close proximity to the foothills of the Rockies shows that the validity of Kendrew's statement depends on the season of the year. Thus it was found, for instance, that the 31 stations in British Columbia received average six-month totals of only 10.83 inches between April and September, while the 28 stations in Alberta average 14.04 inches during the same six-month period.

This study presents a simple model based on a quasi-linear relationship between precipitation and elevation. This model is obviously incapable of dealing with a system of such great complexity. Even so, it appears safe to say that the precipitation estimates derived from this simple model are appreciably better than pure guesswork.

---

[2] G.H. Muttitt, "Spring and Summer Rainfall Patterns in Alberta". Canada, Department of Transport, Meteorological Branch, CIR-3512, 1961, p. 1.

CHAPTER I

THE RELATION OF PRECIPITATION TO TOPOGRAPHY IN THE ROCKIES AND THE INTERPROVINCIAL BOUNDARY REGIONS OF ALBERTA AND BRITISH COLUMBIA.

Introduction

This is an attempt to investigate the relation of topographic features to the variation in precipitation in the Rocky Mountain region of Alberta and British Columbia. In the area of interest of this study, continuous records* for the thirty-year period 1931-1960 were available for 28 stations in Alberta and 31 stations in British Columbia. All available records have been analyzed with a view to determine what relation exists in the Rockies between the amount of precipitation and the physical features of the stations at which it is recorded.

Figure 1-1 shows the mountainous regions considered in this investigation, a strip some 150 miles wide, and extending from the forty-ninth to the fifty-fourth parallel. The main orographic systems, the Rocky Mountains, Selkirks and Purcell Mountains, run generally from southeast to northwest, forming an almost continuous wall of ridges, separated by deep valleys and narrow passes. The highest and most rugged terrain is found along the interprovincial boundary, the Continental Divide, with many peaks rising above ten thousand feet; the highest of these, Mount Robson, has an altitude of 12,972 feet.

Very few precipitation data are available for the higher elevations. Various estimates of precipitation distribution have been made in the past, and a number of isohyetal maps are available for this area, but they are almost certainly subject to drastic revision

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*Not all records are complete.

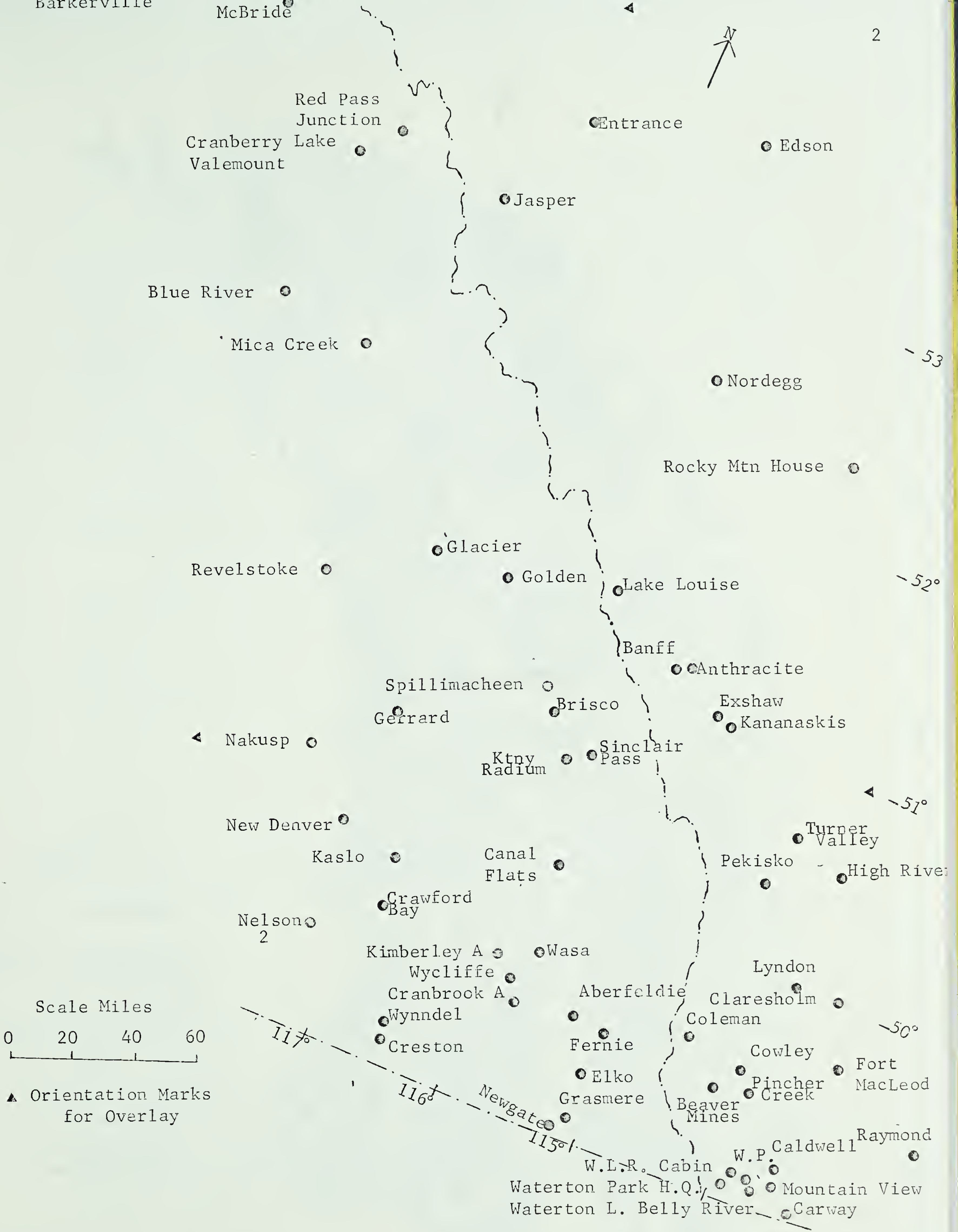

Fig. 1-1 Map showing location of precipitation stations for the Alberta and British Columbia study areas

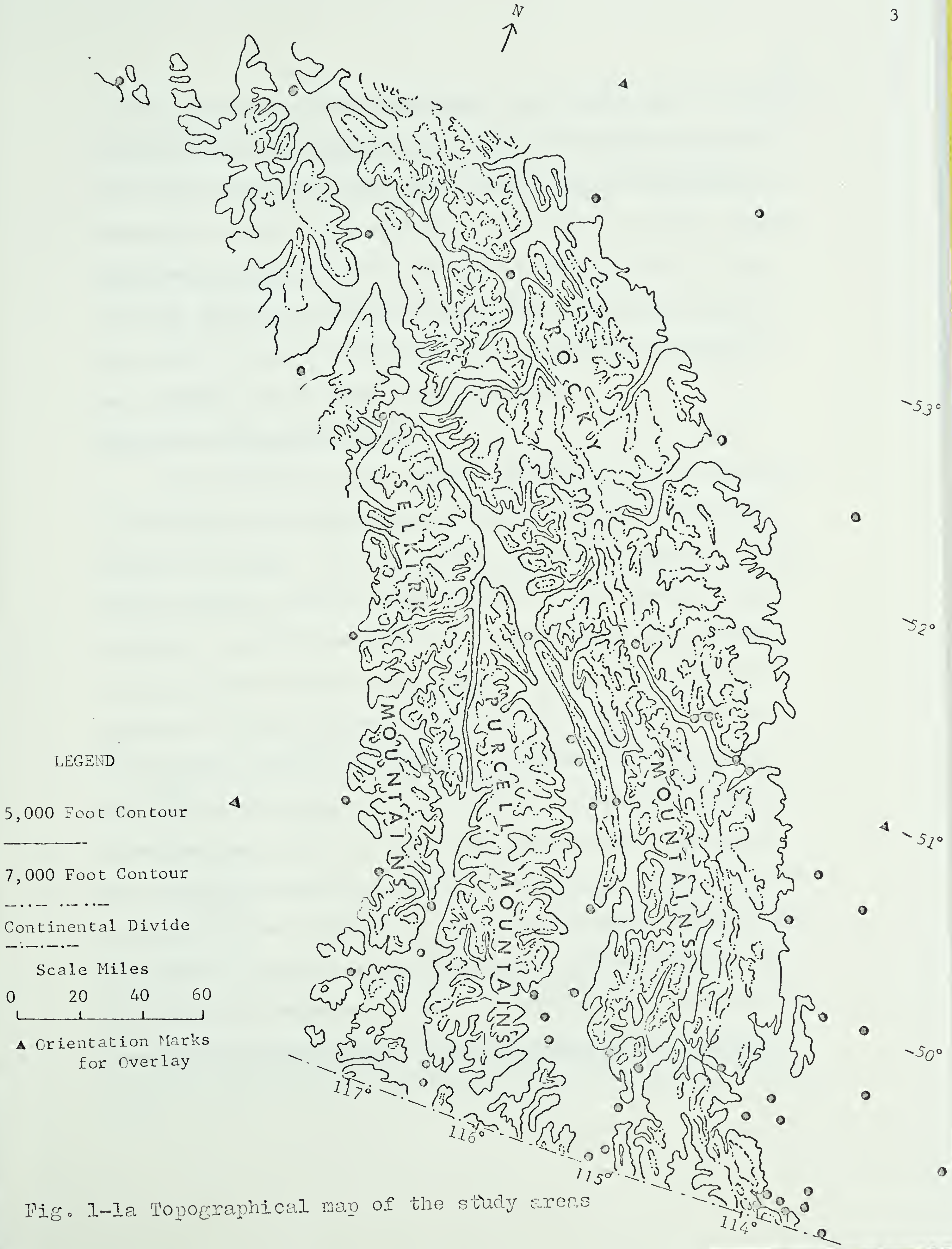

Fig. 1-1a Topographical map of the study areas

as more information becomes available. It is evident that in mountainous areas there will always be considerable uncertainties as to how the isohyets should be drawn, and the precipitation distribution be reasonably estimated. For instance, is it enough to assume a simple relationship between elevation and precipitation in order to deduce isohyetal patterns in regions of sparse data? Experience has shown that this is a rather doubtful practice. A detailed examination of such problems will be given in later sections.

Selection of Records for Study

It is desired to find a rational approach to areal distribution of precipitation in mountainous areas from the comparatively small number of stations. In the area under study the stations are rather widely scattered, and the records of most of these stations are incomplete, a complication which renders the analysis more difficult. In the following analysis use was made of all available data for 31 stations in British Columbia and 28 stations in Alberta. All the precipitation records were examined to determine their continuity and length, the geographical location of the station, its elevation above mean sea level, the slope of the ground surface, its exposure, and the annual normal precipitation. The location of the 59 stations used is presented in Figure 1-1. The stations density computed from the number of stations is approximately one station for 880 sq. mi. The topographic parameters, other than elevation, were obtained from maps prepared by the Surveys and Mapping Branch, scale 1:500,000.

The data available for this analysis may be too small a sample to represent the true relationship; however, it still provides a first measure, subject to further improvement when more data become available.

Normal Precipitation

The precipitation (rainfall, snow) recorded in each month, during the 1931-1960 period, at each station, was abstracted from Precipitation Normals[1]. The monthly and yearly normals are shown in Tables A-3 and A-4 (Appendix A). Reference to these tables shows that the precipitation at these stations ranges from 15.70 inches to 42.31 inches in Alberta and 14.66 inches to 62.17 inches in British Columbia. The frequency distribution of these normals is given in Tables 1-1 and 1-2.

Table 1-1

Precipitation Summary for Stations in Alberta

Range in inches	Total Number	Percentage of total number
15-19.99	10	36
20-24.99	10	36
25-29.99	4	14
30-34.99	1	3.5
35-39.99	2	7
40-44.99	1	3.5

---

[1] Canada, Meteorological Branch, Climatology Division, Precipitation Normals for Alberta and British Columbia (1931-1960). Toronto, 1965.

Table 1-2

Precipitation Summary for Stations in British Columbia

Range in inches	Total Number	Percentage of total number
10-14.99	1	3
15-19.99	12	40
20-24.99	5	16
25-29.99	4	13
30-34.99	3	9.5
40-44.99	3	9.5
45-49.99	1	3
55-59.99	1	3
60-64.99	1	3

Elevation

In mountainous regions, air masses are forced to rise as they pass over a solid barrier[2], and the lifting process results in cooling of the moist air at the rate of about 10 degrees C. per km. change in elevation until saturation is reached, and at the moist adiabatic rate thereafter. Since the condensation process depends on the amount and rate of lifting, the chance for condensation to take place is greater, the higher the elevation. But no simple precipitation-elevation relationship is capable of describing the precipitation distribution observed in mountainous regions.

The direct effect, if any, of elevation on precipitation was examined first. Referring to Appendix A, Tables A-1 and A-2, it is seen that the station elevations range from 3,033 feet to 5,032 feet

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[2] I. Burns, "Small-Scale Topographic Effects on Precipitation Distribution in San Dimas Experimental Forest". Trans. Amer. Geophys. Union, Vol. 34, 1953, pp. 761-767.

in Alberta and from 1,497 to 4,180 feet in British Columbia. The elevation data are summarized below in two tables of frequency distribution of station heights in 500 foot intervals, Table 1-3 and 1-4.

Table 1-3

Elevation Summary for Stations in Alberta

Range in feet	Total Number	Percentage of Total Number
3000-3500	7	25
3501-4000	5	18
4001-4500	11	39
4501-5000	4	14
5001-5500	1	4

Table 1-4

Elevation Summary for Stations in British Columbia

Range in feet	Total Number	Percentage of Total Number
1000-1500	2	6.5
1501-2000	5	16
2001-2500	6	19
2501-3000	8	26.5
3001-3500	6	19
3501-4000	2	6.5
4001-4500	2	6.5

As a first step, the techniques of regression analysis and multiple correlation were used to analyse the annual precipitation data for the 59 stations; the results of this analysis are shown below. Two linear regression equations relating elevation to precipitation were derived from the data given in Appendix A.

$$P = 0.82 + 5.5\,E \qquad \text{for Alberta}$$

$$P = 27.4 - 0.26\,E \qquad \text{for British Columbia}$$

Precipitation, P, is expressed in inches and elevation, E, in thousands of feet. Tables 1-5 and 1-6 are summaries of the means, standard deviations, maxima, minima, and correlation coefficients for the stations which were used in developing the regression relation.

Table 1-5

Statistical Summary for Alberta (28 Stations)

	Mean	Std. Dev.	Min.	Max.
Precipitation(in.)	23.03	6.62	15.70	42.31
Elevation(1000 ft.)	4.04	0.53	3.033	5.032
Correlation Coefficient		0.44		

Table 1-6

Statistical Summary for British Columbia (31 Stations)

	Mean	Std. Dev.	Min.	Max.
Precipitation(in.)	26.77	12.41	14.66	62.17
Elevation(1000 ft.)	2.66	0.71	1.497	4.18
Correlation Coefficient		-0.015		

When precipitation is plotted against elevation, (see Figures 1-2, 1-3) the association of annual precipitation with elevation is seen to be poor. The computed correlation coefficients are 0.44 and -0.015 respectively for Alberta and British Columbia, indicating that there is almost no association between the two parameters. Station elevation alone does not explain much of the variation in

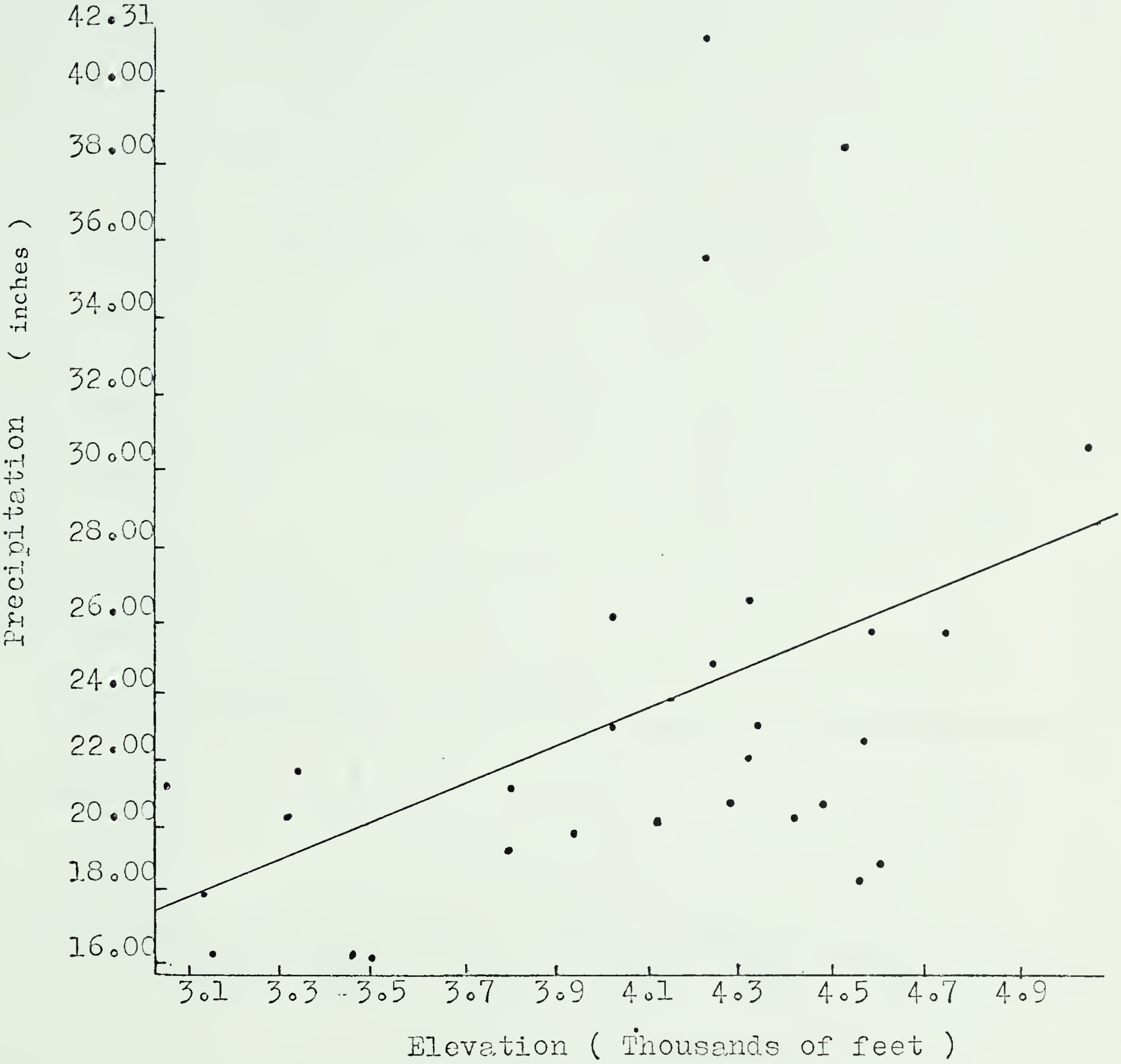

Fig. 1-2 Precipitation versus Elevation for 28 Alberta Stations

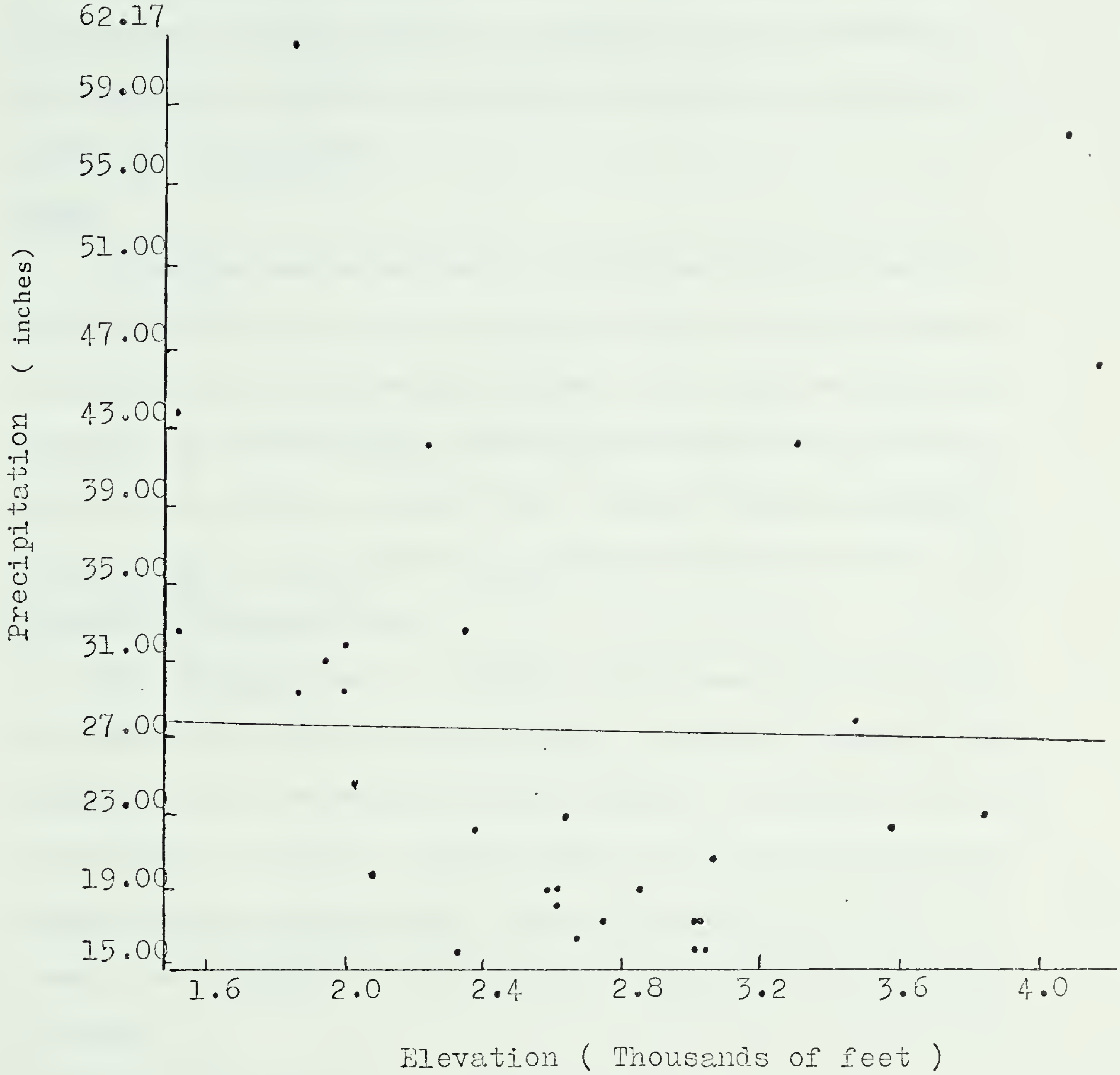

Fig. 1-3 Precipitation versus Elevation for 31 British Columbia Stations

precipitation[3].

Therefore we may conclude that the present results from the 28 stations in Alberta and the 31 stations in British Columbia do not provide much evidence for assuming an association between elevation and precipitation.

Slope

Since the results obtained by simple precipitation-elevation correlation were very poor, an attempt was made to obtain a better relation by introducing another parameter, the slope, as defined by Spreen[4]. He defined slope as the maximum relief within a maximum radius of five miles, centered at the station, and measured along a line normal to the contours and passing through the station , expressed in thousands of feet.

Air flowing normal to a steeply sloping mountain will be lifted more rapidly than air flowing normal to gradually sloping mountain. Since the rate at which water vapour condenses is related to the rate at which air is lifted, a greater amount of precipitation could be expected on the steeper slopes. With this parameter taken into account, the following two multiple linear regression equations were obtained:

---

[3] E.R. Reinelt, "The Effect of Topography on the Precipitation Regime of Waterton National Park". The Alberta Geographer, No. 4, 1968, pp. 19-30.

[4] W.C. Spreen, "A Determination of the Effect of Topography upon Precipitation". Trans. Amer. Geophys. Union, Vol. 28, 1947, pp. 285-290.

$$P = 2.79 + 4.87\ E + 1.02\ S \qquad \text{for Alberta}$$

$$P = 20.66 + 0.18\ E + 4.69\ S \qquad \text{for British Columbia}$$

where slope, S, is expressed in thousands of feet.

Tables 1-7 and 1-8 show statistical summaries of means, standard deviation, correlation, and regression coefficients for the three parameters, precipitation, elevation and, slope for Alberta and British Columbia.

Table 1-7

Statistical Summary for Alberta

	Mean	Std. Dev.	Correlation	Regression Coefficient
Precipitation(in.)	23.03	6.62		
Elevation(1000 ft.)	4.04	0.53	0.44 (E vs P)	4.9
Slope(1000 ft./mi.)	0.56	0.58	0.31 (S vs P)	1.02
Multiple Correlation		0.45		
Std. Error of Estimate		6.15		

Table 1-8

Statistical Summary for British Columbia

	Mean	Std. Dev.	Correlation	Regression Coefficient
Precipitation(in.)	26.77	12.41		
Elevation(1000ft.)	2.66	0.71	-0.015 (E vs P)	0.18
Slope(1000ft./mi.)	1.20	0.56	0.21 (S vs P)	4.7
Multiple Correlation		0.21		
Std. Error of Estimate		12.5		

Relating precipitation to elevation and slope shows no significant difference when compared with the precipitation-elevation

relation alone.

Exposure

The final parameter examined was exposure, defined as the sum of the sectors of a one mile circle, centered at the station, in which there were no topographic features of height in excess of, or equal to the height of the station[5]. This is expressed in degrees. An examination of the stations for the area of interest indicated that there was practically no measurable improvement in correlation. Another definition of exposure, similar to that defined by Rodda[6], was investigated, with little success. Spreen defined exposure as the sum of those sectors of a 20-mile radius circle, centered at the station, not containing a barrier 1,000 feet or more above the station elevation[7]. Rodda applied his definition of exposure to the region of the River Ystwyth Catchment where the terrain is quite flat, compared to the Rocky Mountain regions. The gauges were located at representative sites varying in elevation from 25 to 1,500 feet in the area of his study. The multiple correlation coefficient was improved appreciably by using the exposure as a parameter. However, Rodda's definition of exposure is suitable only for regions with minor relief, but not adequate for the Rocky Mountain regions. Most of the stations

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[5] J.C. Rodda, "An Objective Method for the Assessment of Areal Rainfall Amounts". Weather 17(2), 1962, pp. 54-59.

[6] *Loc. cit.*

[7] Spreen, *op. cit.*, p. 285 ff

in the Rocky Mountains are surrounded by high ground of rugged topography. Thus the results are still unsatisfactory and little is gained by using this parameter in the analysis.

Conclusion

Analysis of the precipitation records of the 59 stations located along the Alberta-British Columbia boundary regions indicates that a simple definite relation between elevation and precipitation does not exist in this particular area under the assumption that the two sets of stations belong to a single precipitation groups.

When both slope and exposure are taken into account, the correlation was not measurably improved, showing that neither effect was very influential in this area. It seems, therefore, that the selected parameters do not represent the significant causal factors adequately, or may be too localized to measure the true effects.

CHAPTER II

MONTHLY PRECIPITATION DISTRIBUTION AND VARIATION

Method of Calculation

Inspection of the monthly precipitation data revealed some interesting variation in the amounts for the area of study.

The monthly means for Alberta and British Columbia were found by averaging the data of the 28 Alberta stations, and the 31 British Columbia stations. The maximum and minimum values were selected from the highest and lowest monthly precipitation amounts of the two groups of stations. The graphs of the monthly precipitation distribution have been normalized.

Average Precipitation Amounts

i) Alberta discussion:

The curve for Alberta (Figure 2-1 indicates that there is very little precipitation during the winter season from October to March. During April the curve rises sharply until it reaches a maximum in June. During July the average precipitation amounts decrease, but recover in August forming a second maximum. Values decline during September and October to the low monthly precipitation amounts which characterize the winter months.

ii) British Columbia discussion:

The average monthly precipitation amounts in British Columbia (refer to Figure 2-1) indicate that the onset of heavy precipitation comes in September. Maximum precipitation comes during the month of December and declines rapidly thereafter, falling to a minimum by April.

During the warm[1] months the precipitation pattern for British Columbia is similar to that of Alberta, the main difference being that the amplitude of the British Columbia precipitation is somewhat lower.

During the summer the area of maximum precipitation lies to the east of the Rocky Mountain Range. Monthly precipitation averages for the individual stations range from 1.88 inches to 3.62 inches, and the April to September six month total is 14.04 inches. Thus the Alberta stations record on the average 3.21 inches more precipitation between April and September than the British Columbia stations.

In the winter months the situation reverses. British Columbia records a total of 15.95 inches of precipitation for the remaining six months in contrast to the 8.99 inches recorded by the Alberta stations for the same period. Alberta has on the average 6.96 inches of precipitation less during the winter than British Columbia.

Table 2-1

Monthly Average Precipitation (inches)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Alberta	1.45	1.47	1.54	2.00	2.45	3.62	1.97	2.12	1.88	1.54	1.49	1.50
British Columbia	3.21	2.31	1.83	1.46	1.80	2.44	1.60	1.75	1.78	2.38	2.81	3.41

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[1] April to September inclusive.

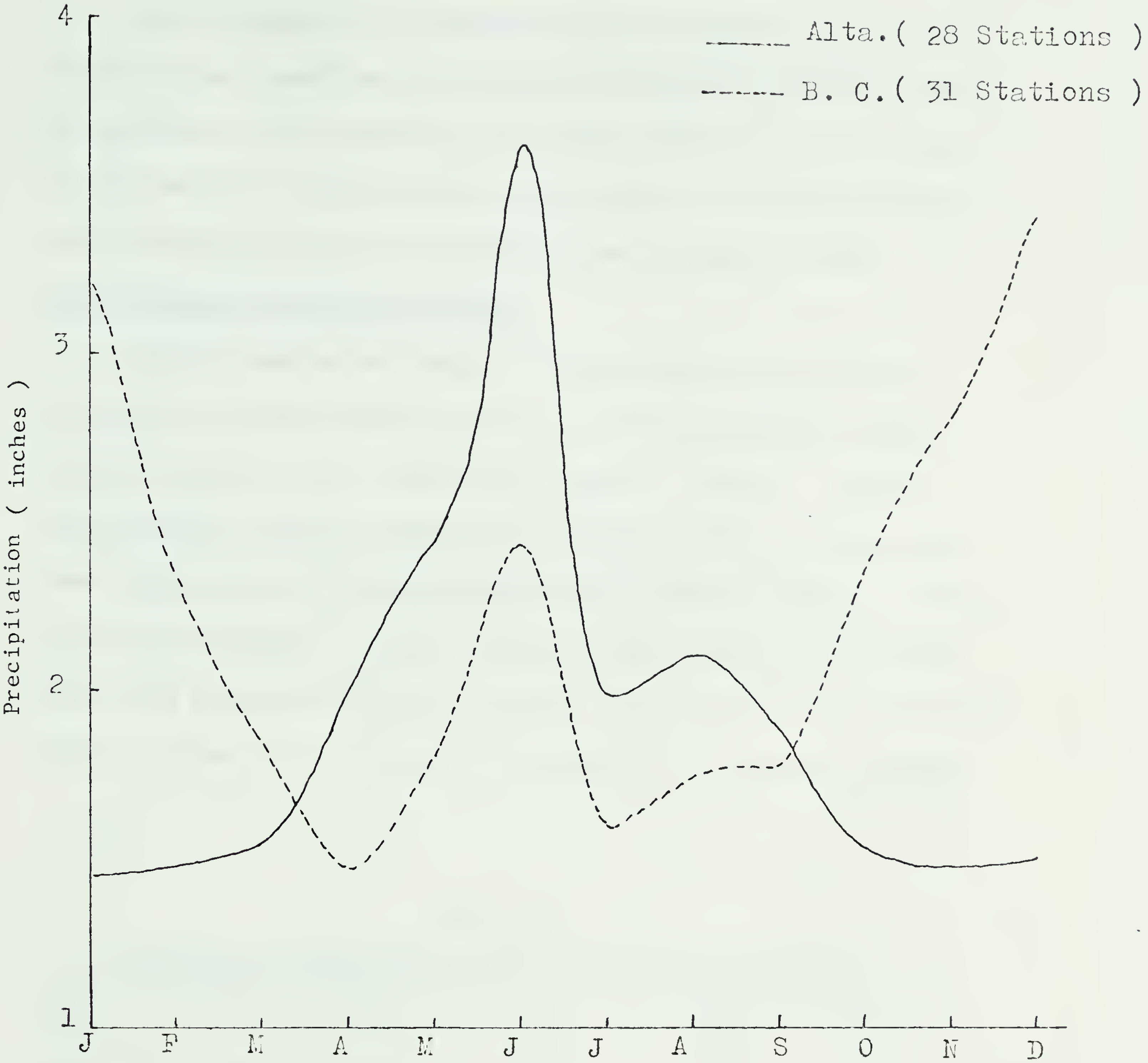

Fig. 2-1 Monthly average precipitation curves for the Alberta and British Columbia study areas

We can summarize by concluding that a summer-wet, winter-dry climate occurs immediately to the east of the Rocky Mountain Range in contrast to the summer-dry, winter-wet climate just to the west of the Rockies. Generally the western side of the Rocky Mountains receives more precipitation annually than the eastern side.

Local Minimum Precipitation Regime

Another interesting feature of the minimum precipitation pattern in British Columbia points out some geographical causes for the minimum amounts occurring in specific regimes. Golden, Spillimacheen, Wycliffe, Kimberley A, Grasmere, Wasa, Newgate, and Canal Flats record the lowest monthly precipitation amounts in eastern British Columbia. Their elevations range from 2,325 to 3,050 feet while their precipitation amounts range from 0.36 to 1.54 inches Table 2-2 shows the locations of the monthly precipitation minimum.

Table 2-2

Locations of Monthly Precipitation Minimum (inches)

Jan	Feb	Mar	Apr	May	June
1.25	0.73	0.36	0.75	1.13	1.54
Canal Flat	Grasmere	Spillimacheen	Kimberley A	Golden	Golden
July	Aug	Sept	Oct	Nov	Dec
0.73	0.92	0.90	0.75	1.13	1.47
Kimberley A	Newgate	Kimberley A	Wycliffe	Wasa	Wasa

These stations are situated in a stream valley with the Rocky Mountain Range to the east and the Purcell Range to the west. Since these stations lie in a valley they appear to be in the "rain-shadow" of both mountain ranges. The fact that some of the low-lying stations in a broad basin, such as the Kootenay River region, receive less precipitation may be attributed to their being shielded to some degree from storms crossing the mountain ranges.

Horton in 1924, following an investigation in the Catskills stated:[2]

> "If a stream valley is so oriented that the prevailing rain-bearing winds blow across rather than with the streams, then records for rain gauges located in the valleys may show no consistent relation to their actual elevations, although there may be a general increase in precipitation with elevation for the basin as a whole."

Consequently, stations in the low-lying part of a valley may receive much the same amount of precipitation as a much higher station on the margin of the valley. For air flow perpendicular to the valley, the total precipitation catch at such stations is a function of the highest or most dominant elevation over which the moist air masses must pass to reach the stations rather than a function of the elevation of the individual stations.

For the valley under consideration a scattergram was plotted

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[2] R.E. Horton, "Determining the Mean Precipitation on a Drainage Basin". New England Water Works Association Journal, 38(1): 1924, pp. 1-43.

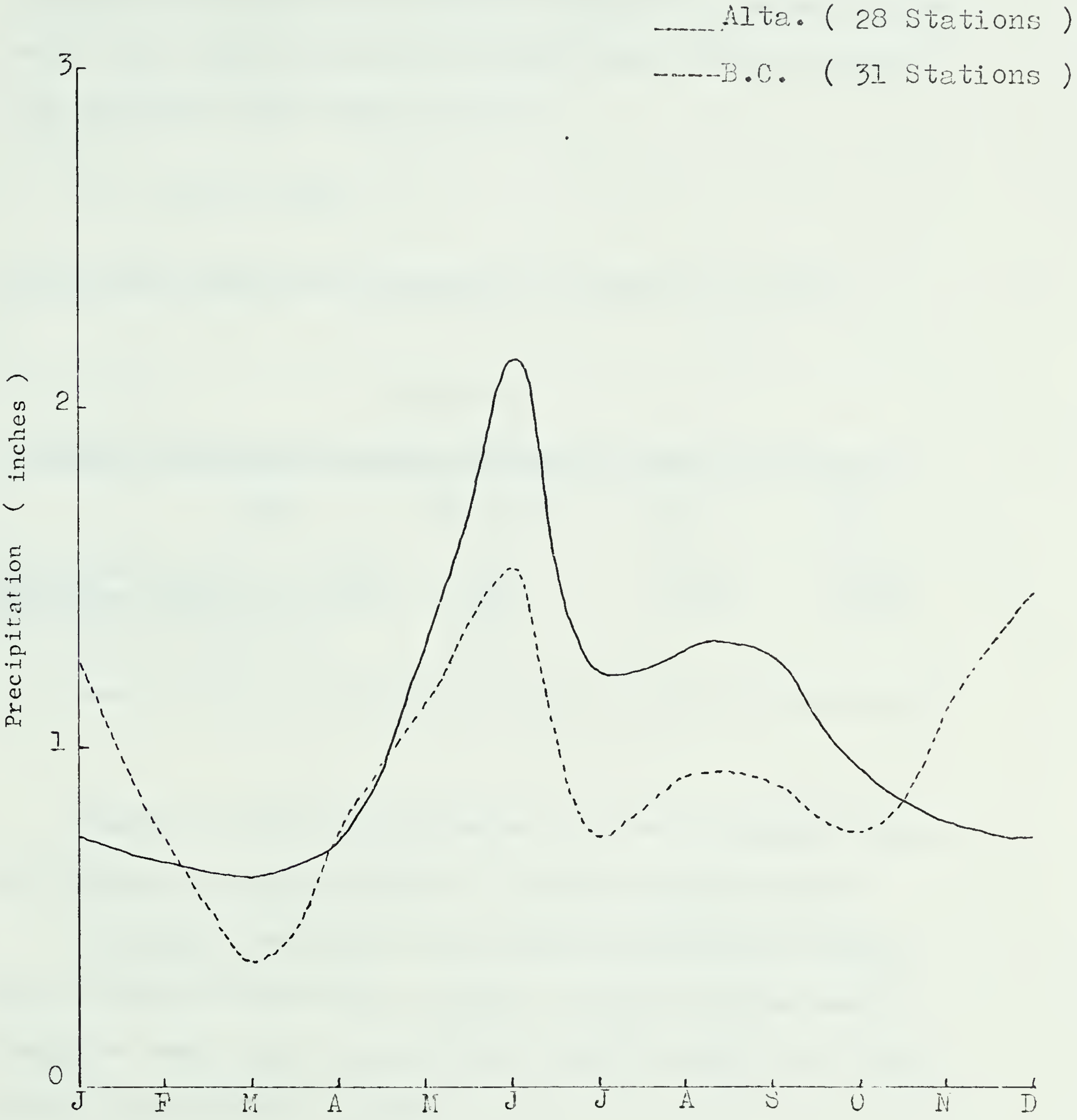

Fig. 2-2 Monthly minimum precipitation curves for the Alberta and British Columbia study areas

of precipitation amounts versus elevation. The plot indicates that a negative correlation exists between precipitation amount and elevation. The regression equation derived from the data recorded in this particular valley takes the form:

$$P = 18.7 - 0.8 E$$ [3]

showing that precipitation decreases as elevation increases.

Table 2-3

Summary of the Means, Standard Deviation, Maximum and Minimum

	Mean	Std. Dev.	Min.	Max.
Precipitation (in.)	16.48	1.33	14.66	18.45
Elevation (1000 of ft.)	2.786	0.24	2.325	3.050
Correlation Coefficient		-0.15		

Figure 2-2a shows the regression line and the scatter diagram for 10 British Columbia stations in the Rocky Mountain Trench.

In Alberta, the sites of the monthly precipitation minimum are not clearly defined and localized, but appear concentrated at Jasper for March, April, May and June. Table 2-4 gives the monthly minimum precipitation in Alberta.

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[3] Precipitation, P, is expressed in inches and elevation, E, in thousands of feet.

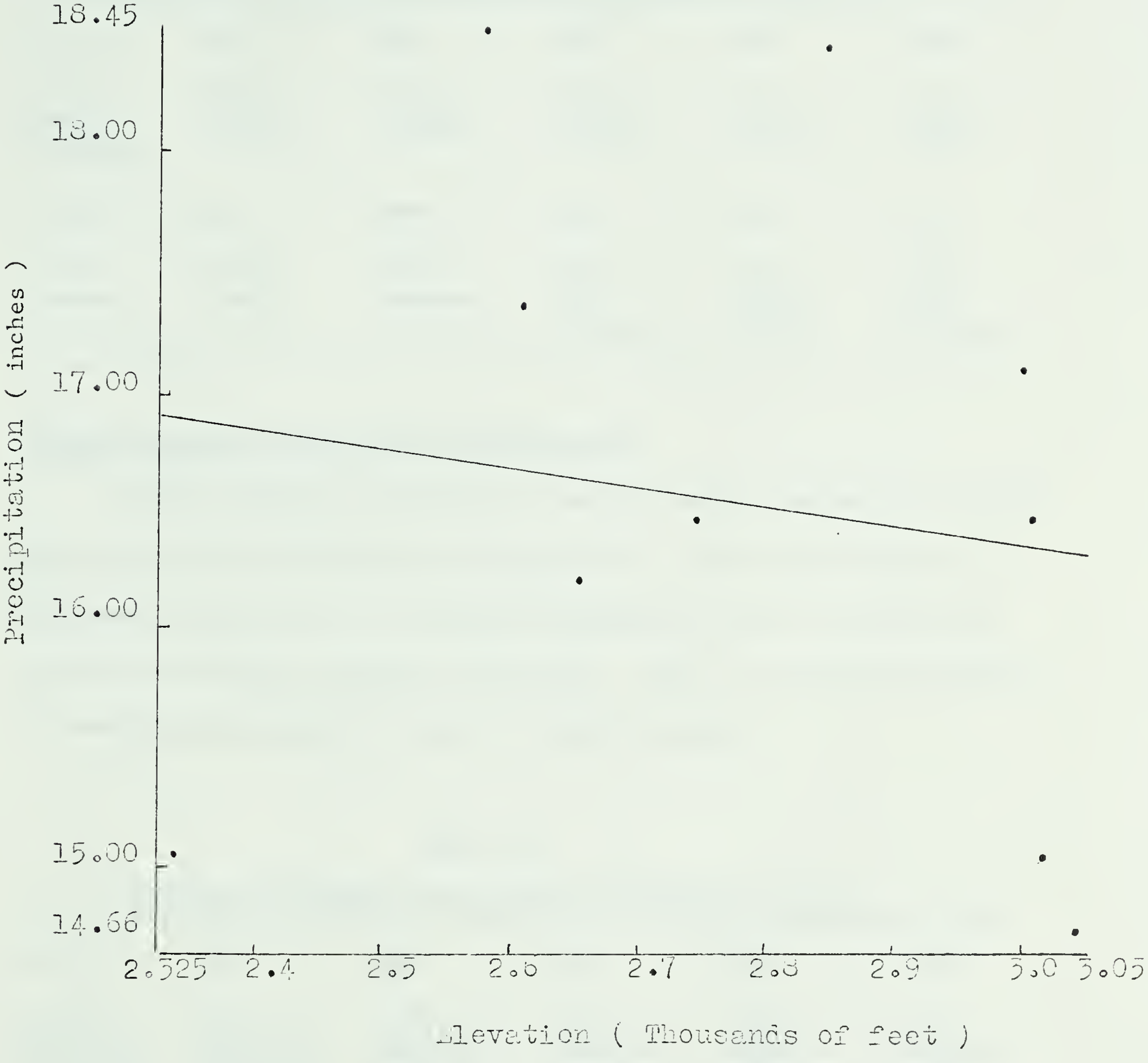

Fig. 2-2a Precipitation versus Elevation for 10 (B.C.) stations in the Rocky Mountain Trench

Table 2-4

Locations of Monthly Precipitation Minimum (inches)

Jan	Feb	Mar	Apr	May	June
0.73	0.67	0.63	0.73	1.31	2.15
Fort MacLeod	Exshaw	Jasper	Jasper	Jasper	Jasper
July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1.21	1.30	1.28	0.94	0.78	0.75
Raymond	Cowley	Raymond	Fort MacLeod	Turner Valley	Fort MacLeod

Maximum Monthly Precipitation Distribution

Monthly maximum precipitation amounts appear concentrated around Waterton Park HQ and Waterton Lakes Belly R. Both are situated in Southern Alberta near the mountains, consequently they are both subjected to a strong orographic influence. Table 2-5 lists the location of monthly precipitation maxima in Western Alberta.

Table 2-5

Locations of Monthly Precipitation Maximum (inches)

Jan	Feb	Mar	Apr	May	June
4.44	4.11	3.68	4.43	3.98	5.52
Waterton Park HQ	Waterton Park HQ	Waterton Park HQ	Waterton Park HQ	Waterton Lakes Belly R.	Waterton Lakes Belly R.
July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
3.66	3.40	3.02	3.27	3.52	4.14
Edson	Turner Valley	Waterton Lakes Belly R.	Waterton Park HQ	Waterton Park HQ	Lake Louise

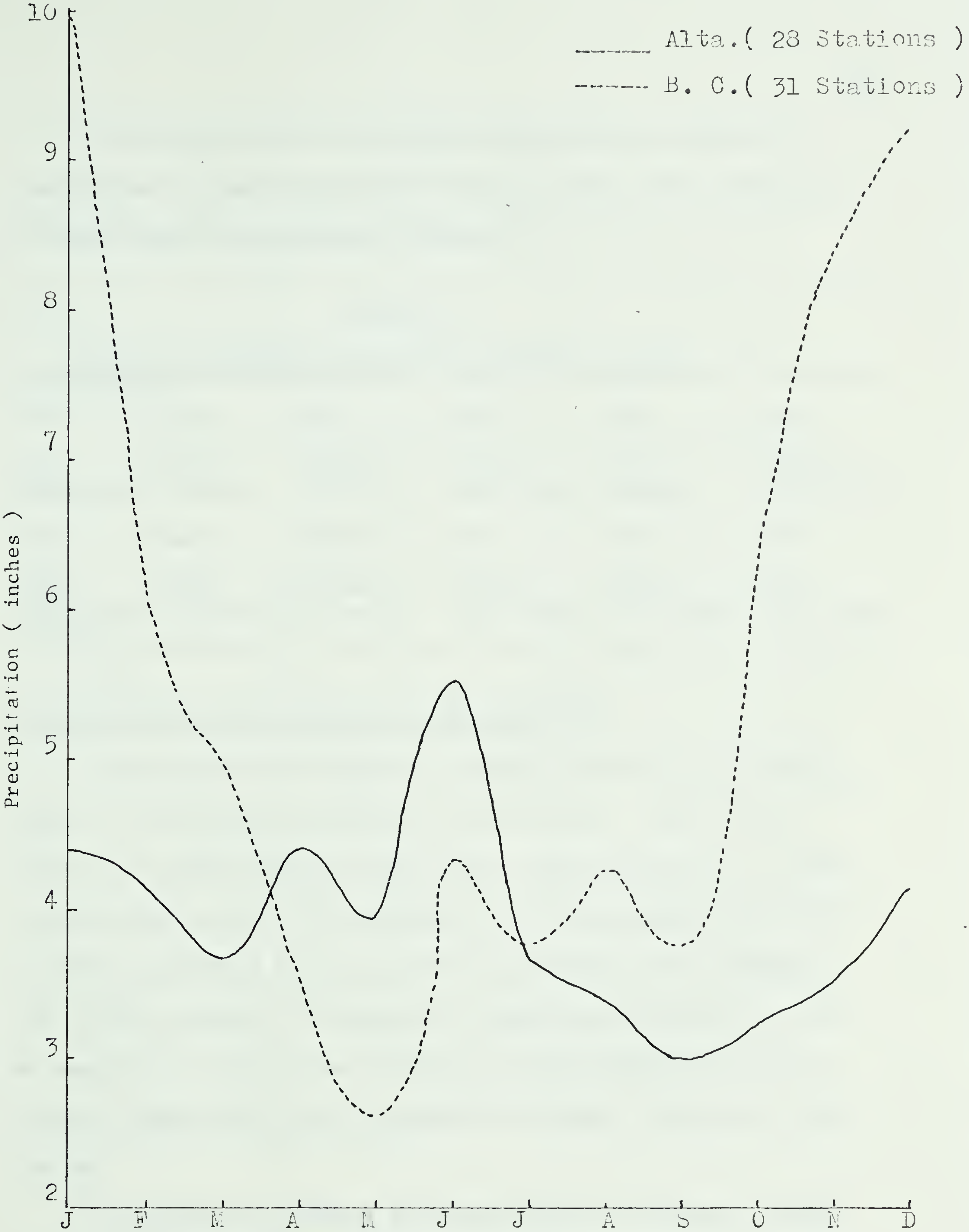

Fig. 2-3 Monthly maximum precipitation curves for the Alberta and British Columbia study areas

In British Columbia the monthly precipitation maxima are concentrated in the northern part of the province. The locations of these maxima are displayed in Table 2-6.

Table 2-6

Locations of Monthly Precipitation Maximum (inches)

Jan	Feb	Mar	Apr	May	June
9.95 Mica Creek	6.07 Glacier	4.99 Glacier	3.58 Mica Creek	2.63 Nakusp	4.36 Barkerville
July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
3.78 Barkerville	4.27 Barkerville	3.74 Glacier	6.33 Mica Creek	8.33 Mica Creek	9.24 Mica Creek

Relation of Air Flow Direction to Precipitation

The direction of airflow in a mountainous region has a major effect on the amount of orographic precipitation. The Purcell, Selkirk and Rocky Mountain Ranges form a solid barrier for air moveing from west to east. The passage of an air mass over this barrier is often accompanied by precipitation initiated by the orographic lift of the foothills. Consequently, much more precipitation could be expected to occur at low altitudes on the windward side of the foothill regions than would be expected at higher altitudes on the leeside.

The effects of location on precipitation in the same airmass regime, but on the opposite sides of orographic barriers, was examined directly by comparing the precipitation records of pairs of

windward and leeward stations at the same latitude. The results of this comparison are given in Table 2-7, for stations east and west of the Rockies, Selkirks and Purcell mountains. The data clearly show a wet strip along the west side of these mountain ranges, and a dry strip along the eastern sides.

Conclusion

A comparison of monthly precipitation in the Rocky Mountain Range indicates that Alberta has wetter summers than British Columbia. However, the British Columbia stations receive more precipitation annually than the Alberta stations, since they have much wetter winters.

We may also conclude that a north-south valley exhibits the rain-shadow effect, and that valley stations and basins, such as the Kootenay River, show that there is no direct relationship between elevation and precipitation.

Precipitation maxima for British Columbia are found in the northern part of the study area, whereas in Alberta they occur in the southwest. The fact that precipitation maxima occur in different latitudes on opposite sides of the Continental Divide may be attributed to topographic effects on air mass circulation and frontal activity in different seasons.

Table 2-7

Precipitation and Geographic Location

Station	Precip. (in.)	Elevation (ft.)	Location
McBride	21.31	2,360	Fraser River Valley
Entrance	19.98	3,300	East of Rocky Mountains
Cranberry Lake Valemount	18.47	2,600	Fraser River Valley
Jasper	15.98	3,480	East of Rocky Mountains
Blue River	40.84	2,243	Thompson River Valley
Nordegg	21.73	4,300	East of Rocky Mountains
Golden	18.45	2,583	Columbia River Valley
Banff	18.48	4,583	East of Rocky Mountains
Anthracite	18.34	4,550	East of Rocky Mountains
Revelstoke	42.54	1,497	West of Selkirk Mountains
Spillimacheen	17.31	2,615	East of Purcell Mountains
Nakusp	31.34	1,500	West of Selkirk Mountains
Canal Flat	16.15	2,563	East of Purcell Mountains
Kaslo	29.84	1,930	West of Purcell Mountains
Wasa	14.66	3,050	East of Purcell Mountains
Crawford Bay	30.94	2,000	West of Purcell Mountains
Kimberley A.	14.95	3,016	East of Purcell Mountains
Nelson 2	28.62	1,980	West of Purcell Mountains
Cranbrook A.	16.41	3,013	East of Purcell Mountains
Fernie	41.43	3,305	West of Rocky Mountains
Beaver Mines	24.36	4,218	East of Rocky Mountains
Wynndel	23.40	2,050	West of Purcell Mountains
Grasmere	18.34	2,850	East of Purcell Mountains
Creston	18.94	2,085	West of Purcell Mountains
Newgate	15.03	2,325	East of Purcell Mountains

CHAPTER III

HARMONIC ANALYSIS

Introduction

Harmonic analysis is a useful technique for investigating periodicity problems which can provide information about the physical causes which produce the complex periodicity trends. A periodicity problem refers to any empirical parameter which demonstrates fluctuating or cyclic values, such as annual precipitation and temperature.

A variable or function $F(x)$ is said to be periodic with a period T, if, for all x:

$$F(x + T) = F(x).$$

When dealing with meteorological data we are usually considering variables with discrete values, such as monthly means. If $F(x)$ is defined in a certain interval we can account for all values of $F(x)$ by a finite number of sine and cosine terms[1].

In this study we shall look at twelve months of observations. Since we have twelve equally spaced observations, six harmonics will be available to describe the annual variation.

Since each harmonic may be caused by some isolated physical process we shall treat the harmonics independently. We may, for example, find the second harmonic of the precipitation curve to be a function of orographic environment, while other harmonics may be related to individual storm tracks. It is not, however, neces-

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[1] V. Conrad and L.W. Pollak, Methods in Climatology , Harvard University Press, Cambridge, Mass., 1950, p. 119.

sary that each individual harmonic result from different physical causes.

Figures 3-1, 3-2, 3-3, 3-4, 3-5 display some harmonic curves (solid lines); also shown with these curves are actual precipitation curves (dotted line) for ready comparison. Generally, the first two harmonics are sufficient to describe the variation of the periodic function. In this study the first harmonic has a period of one year and is a measure of the annual variations in the actual precipitation curve. Similarily the second harmonic describes the semiannual trend in precipitation. The first harmonic has one crest and one trough, the second harmonic has two crests and two troughs, and so on.

Harmonic analysis of twelve monthly observations yields also the phase angles of six harmonics. Phase angles are measures of the time of occurrence of maxima and minima in the annual precipitation cycle; usually only the first two or three may be physically significant.

Analysis of Individual Stations

Five pairs of precipitation reporting stations were selected for this analysis:

1) Waterton Park HQ and Newgate
2) Lake Louise and Glacier
3) Nordegg and Mica Creek
4) Jasper and Cranberry Lake Valemount
5) Entrance and Barkerville

These pairs were chosen for the following reasons:

(1) The first station of each pair lies in Alberta while the second is in British Columbia.

(2) All stations are close to the Continental Divide with individual members of each pair lying on a line approximately normal to the Divide.

(3) Most of these stations received maximum or minimum precipitation amounts in their particular region.

Harmonic analysis was applied to these station pairs in order to identify likely physical causes for the observed precipitation variations across the Divide.

Topographical Characteristics

In the case of Waterton Park HQ, as Reinelt has stated[2], "Waterton Park HQ at the very foot of the mountains and in the funnels mouth, has the highest annual snowfall (228.5 inches) of any Canadian station east of the Rockies. Its annual rainfall (19.46 inches) is the highest in the Prairie Provinces, and its combined precipitation total of 42.31 inches rivals that of many places east of the Great Lakes". Newgate lies across the boundary in line with Waterton Park HQ along the Kootenay River. The Kootenay Valley runs from northwest to southeast parallel to the mountain ridges,consequently Newgate receives only 15.03 inches of precipitation. Although the ground around Newgate is about 3,000 feet above M.S.L. and the basin is

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[2] Reinelt, op. cit., p. 19 ff.

about 15 miles wide, the observing station is screened by neighbouring mountain peaks which rise to 7,500 feet. Hence Newgate is always in the rain shadow since it is located in a deep wide basin with high peaks surrounding it.

Glacier is located in a deep "well-like" valley, at the base of some high mountains. The average slope in the Glacier area is 1,300 feet per mile. Three peaks surrounding Glacier rise to heights of 9,106, 10,194, and 10,818 feet, respectively. These three peaks form a triangle about 55 square miles in area. The surrounding mountains form a barrier for the air flowing into Glacier independent of wind direction. This does not, however, imply that the precipitation in the "well" will be below average in comparison with some other stations of higher elevation and good exposure. On the contrary, Glacier records one of the highest annual precipitation amounts for the area under study, another instance of the fact that elevation of station and exposure are not sufficient criteria for estimating precipitation in mountainous areas. One possible hypothesis we may make is to assume that there exists a fictitious station directly above the actual station and at the same height as the surrounding peaks. On the basis of this assumption the effective height of the actual station (like Glacier) is thus the same as the average height of the surrounding peaks and greater than the actual heights of other stations in the study area not surrounded by high peaks. Thus a station in a deep, narrow "well" may in fact have better effective exposure, and receive more precipitation than higher

stations not in a well, and of apparently excellent exposure.

Mica Creek resembles Glacier, differing only in its lower elevation and increased precipitation amounts.

Barkerville is located on flat terrain, with no particularly high peaks within a circle of ten-mile radius. It records 45.25 inches annual precipitation and three of British Columbia's monthly precipitation maxima (See Table 2-6).

Harmonic Analysis of the Selected Stations

Figures 3-1, 3-2, 3-3, 3-4, 3-5, contain plots of first and second harmonics and precipitation curves for all stations. Table 3-1 summarizes the means, amplitudes, and phase angles for the five paired stations.

Table 3-1

Harmonic Analysis of the Selected Stations

Station	Waterton Park HQ	Lake Louise	Nordegg	Jasper	Entrance
Mean	3.53	2.53	1.81	1.33	1.70
A_1	0.85	0.70	1.33	0.52	1.22
ϕ_1	41	122	284	248	274
A_2	0.47	0.49	0.58	0.38	0.43
ϕ_2	197	149	112	111	107
	Newgate	Glacier	Mica Creek	Cranberry L. Valemount	Barkerville
Mean	1.25	4.76	5.18	1.54	3.77
A_1	0.27	2.62	3.46	0.42	0.44
ϕ_1	103	109	113	203	146
A_2	0.37	0.78	1.10	0.22	0.58
ϕ_2	152	126	136	150	90

The precipitation curve, for example, for Mica Creek is given by:

$$P = 5.18 + 3.46\,\mathrm{Sin}(30^{o}t + 113^{o}) + 1.10\,\mathrm{Sin}(60^{o}t + 136^{o}) + 0.31\,\mathrm{Sin}(90^{o}t + 226^{o}) + 0.56\,\mathrm{Sin}(120^{o}t + 82^{o}) + 0.52\,\mathrm{Sin}(150^{o}t + 115^{o}) + 0.02\,\mathrm{Sin}(180^{o}t + 89^{o})$$

If we set $t = 0$ this equation will produce the precipitation normal for January. Similarily $t = 1, 2, \ldots\ldots 11$ will give us the monthly precipitation normals from February to December.

Referring to Table 3-1 and Figure 3-1, it is seen that the amplitude of the first harmonic is large for Waterton Park HQ and small for Newgate. Although both stations are under orographic influence the Newgate's amplitude is 0.58 less than Waterton Park HQ's amplitude. Waterton Park HQ has a phase angle of 41^{o} which locates the annual maximum on March 1, while Newgate's phase angle of 103^{o} places the annual maximum in January. The semi-annual variations seems to dominate at Newgate as the second harmonic has greater amplitude than the first harmonic.

The amplitude for Lake Louise's (Fig. 3-2) first harmonic differs by 1.92 from Glacier's amplitude, but there is little difference in phase angle. The phase angle of 122^{o} locates the precipitation minimum for Lake Louise in the first week of June. Glacier, with a phase angle of 109^{o}, reaches its minimum by mid-June. Lake Louise is in fact in the Rockies. It is an exception to the June-maxima so typical of stations east of the Rockies. From the second harmonic we find that Glacier's secondary minima occur in mid-March and mid-

September.

Cranberry Lake Valemount (Fig. 3-3) and Jasper have very similar harmonic wave patterns of but slightly different amplitudes.

Barkerville (Fig. 3-4) displays a complex annual precipitation curve. Barkerville, the highest station (4,180 feet) considered in this study west of the Rocky Mountains, has its second harmonic larger than its first harmonic. It was found that both Barkerville and Newgate, which also has a second harmonic larger than the first, have minima in early March and April, and second minima six months later.

Since Barkerville is situated in the northern part of the area of study in contrast to Newgate which is located in the southern part, it is suggested that the observed component of the second harmonic is a measure of the effects of storm tracks on precipitation amounts.

Comparing the harmonic amplitudes for all stations we observe that Mica Creek (Fig. 3-5) has the largest first and second harmonic although its elevation of 1,860 feet is one of the lowest in the group of stations being studied. We may assume that this curious feature of Mica Creek's precipitation pattern is a result of the effects of the storm tracks and the topographical environment of the area under study.

Table 3-1 demonstrates that all second harmonics for stations west of the Rockies have pronounced mid-March or April minima, followed by second minima six months later.

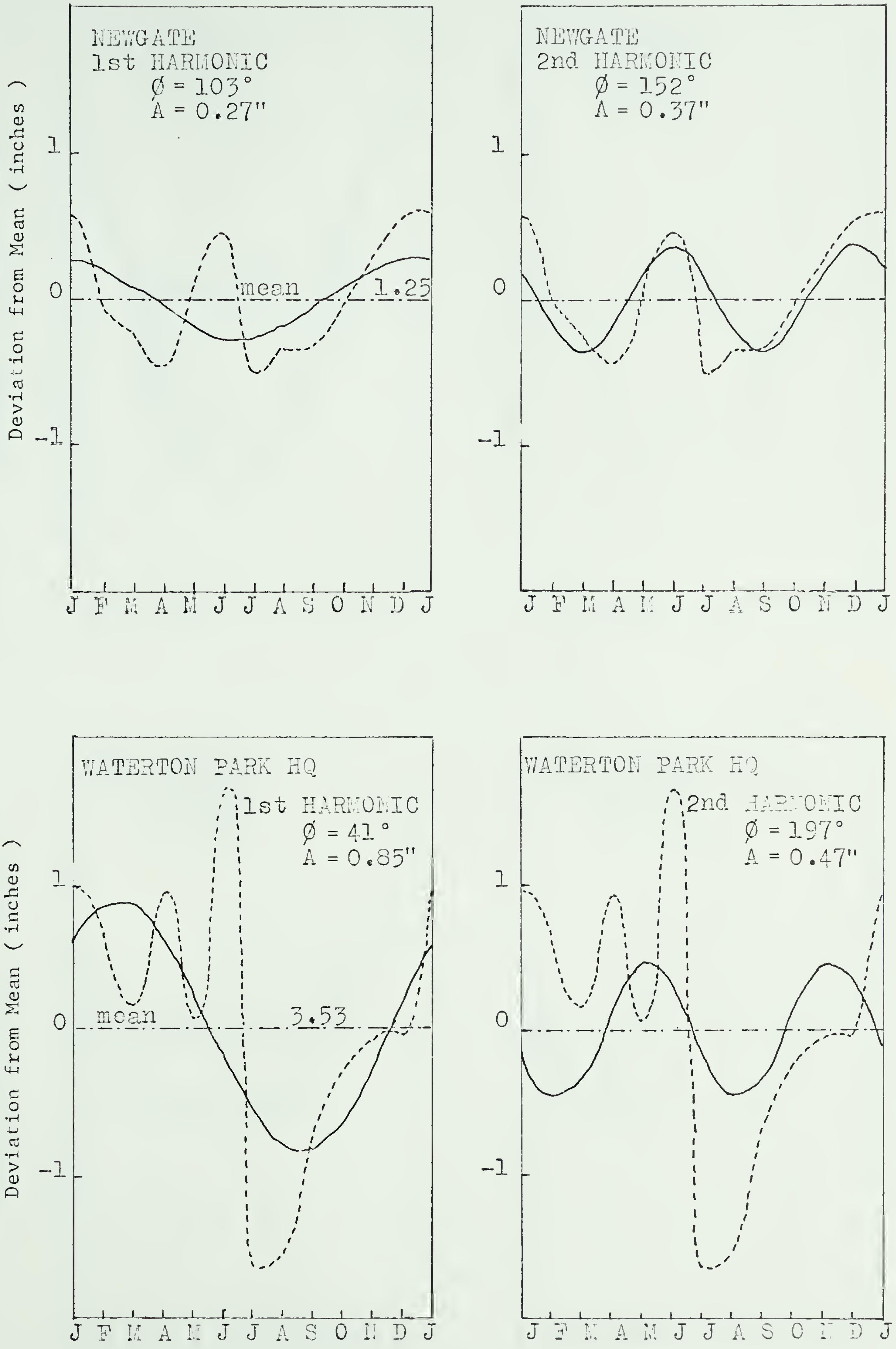

NEWGATE
1st HARMONIC
Ø = 103°
A = 0.27"
mean
1.25
NEWGATE
2nd HARMONIC
Ø = 152°
A = 0.37"
WATERTON PARK HQ
1st HARMONIC
Ø = 41°
A = 0.85"
mean
3.53
WATERTON PARK HQ
2nd HARMONIC
Ø = 197°
A = 0.47"
Deviation from Mean (inches)
1
0
-1
J F M A M J J A S O N D J

Fig. 3-1

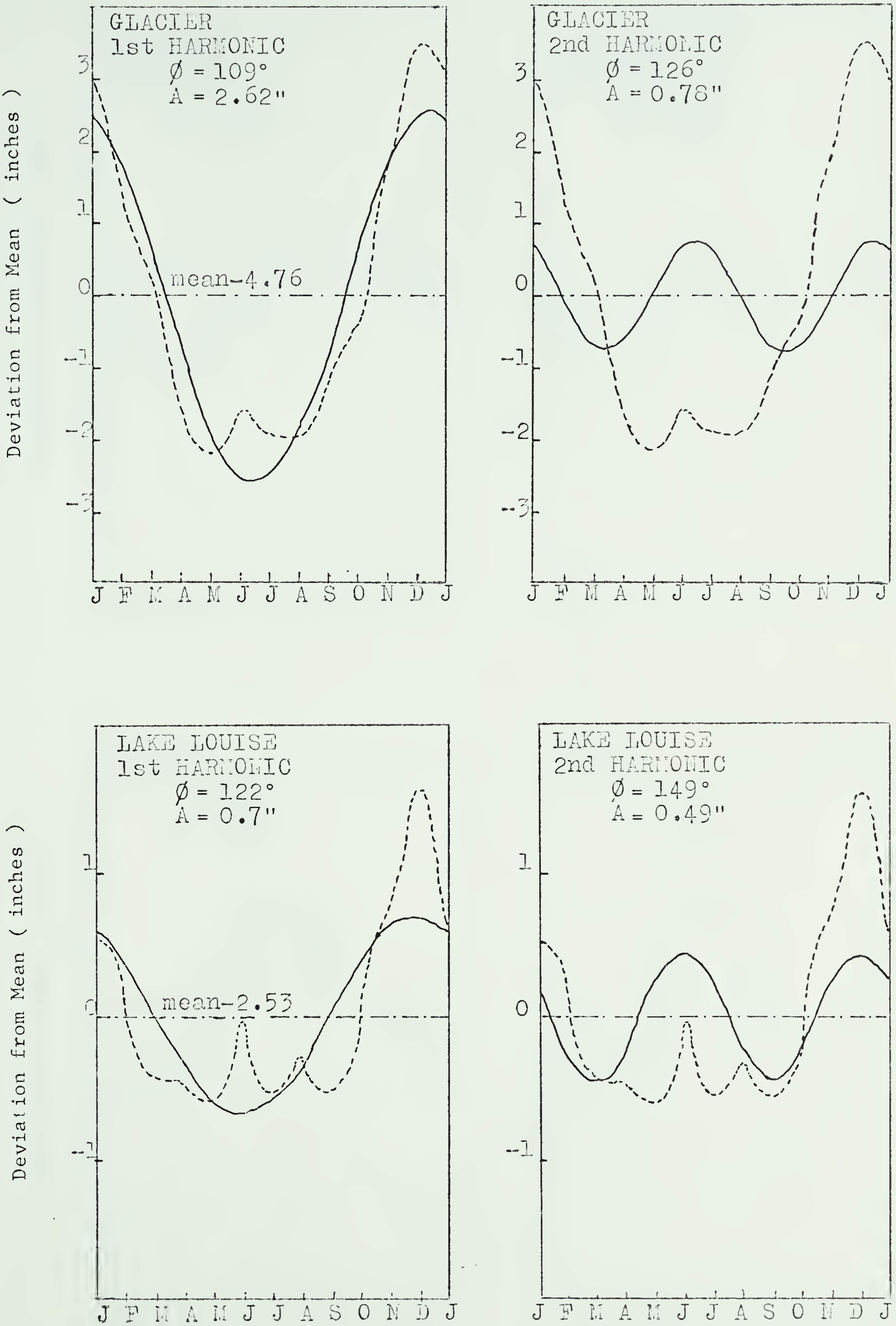

GLACIER
1st HARMONIC
Ø = 109°
A = 2.62"
mean-4.76
GLACIER
2nd HARMONIC
Ø = 126°
A = 0.78"
LAKE LOUISE
1st HARMONIC
Ø = 122°
A = 0.7"
mean-2.53
LAKE LOUISE
2nd HARMONIC
Ø = 149°
A = 0.49"
Deviation from Mean (inches)
3
2
1
0
-1
-2
-3
J F M A M J J A S O N D J

Fig. 3-2

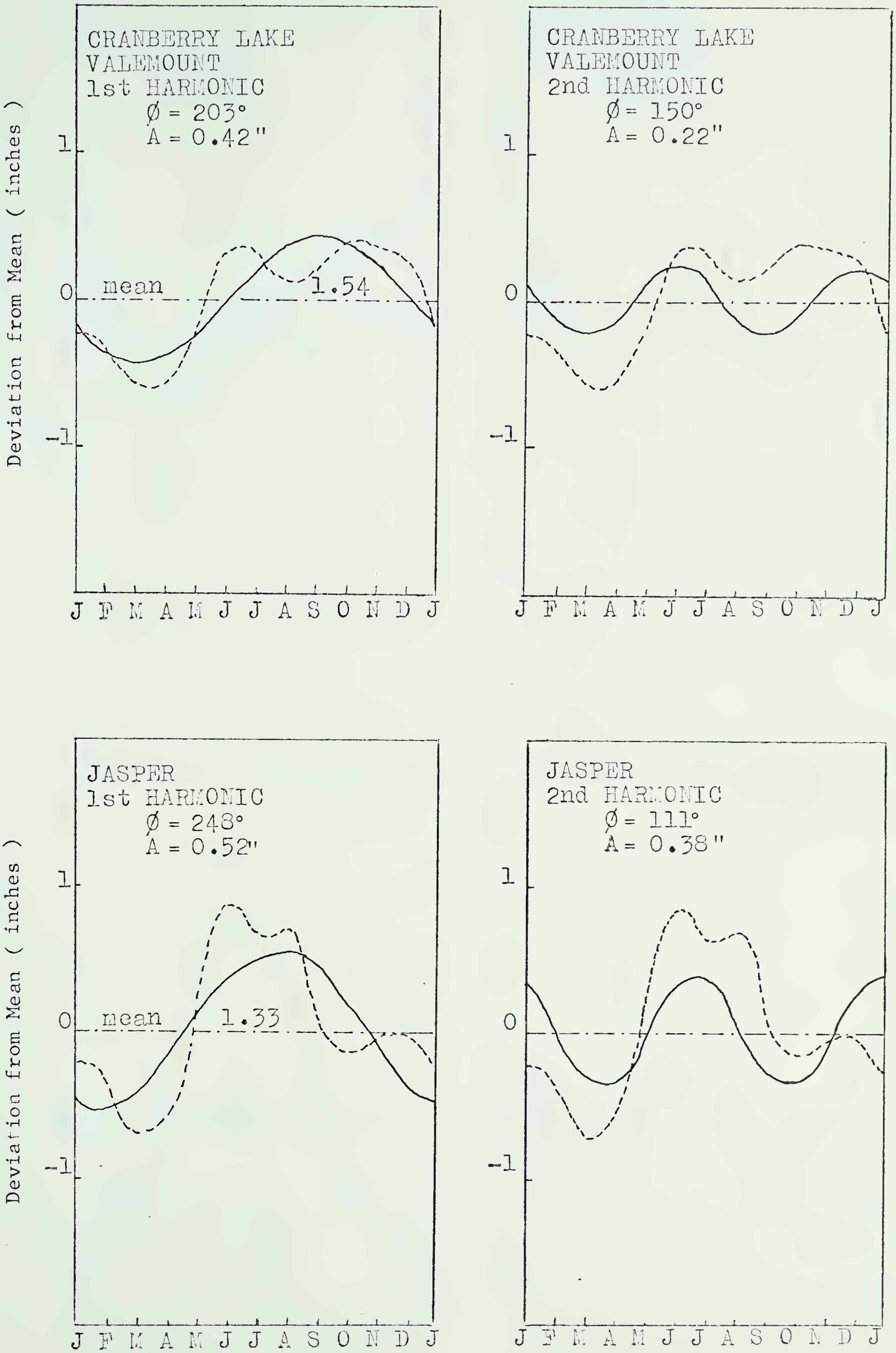

CRANBERRY LAKE
VALEMOUNT
1st HARMONIC
Ø = 203°
A = 0.42"
mean
1.54
CRANBERRY LAKE
VALEMOUNT
2nd HARMONIC
Ø = 150°
A = 0.22"
JASPER
1st HARMONIC
Ø = 248°
A = 0.52"
mean
1.33
JASPER
2nd HARMONIC
Ø = 111°
A = 0.38"
Deviation from Mean (inches)
1
0
-1
J F M A M J J A S O N D J

Fig. 3-3

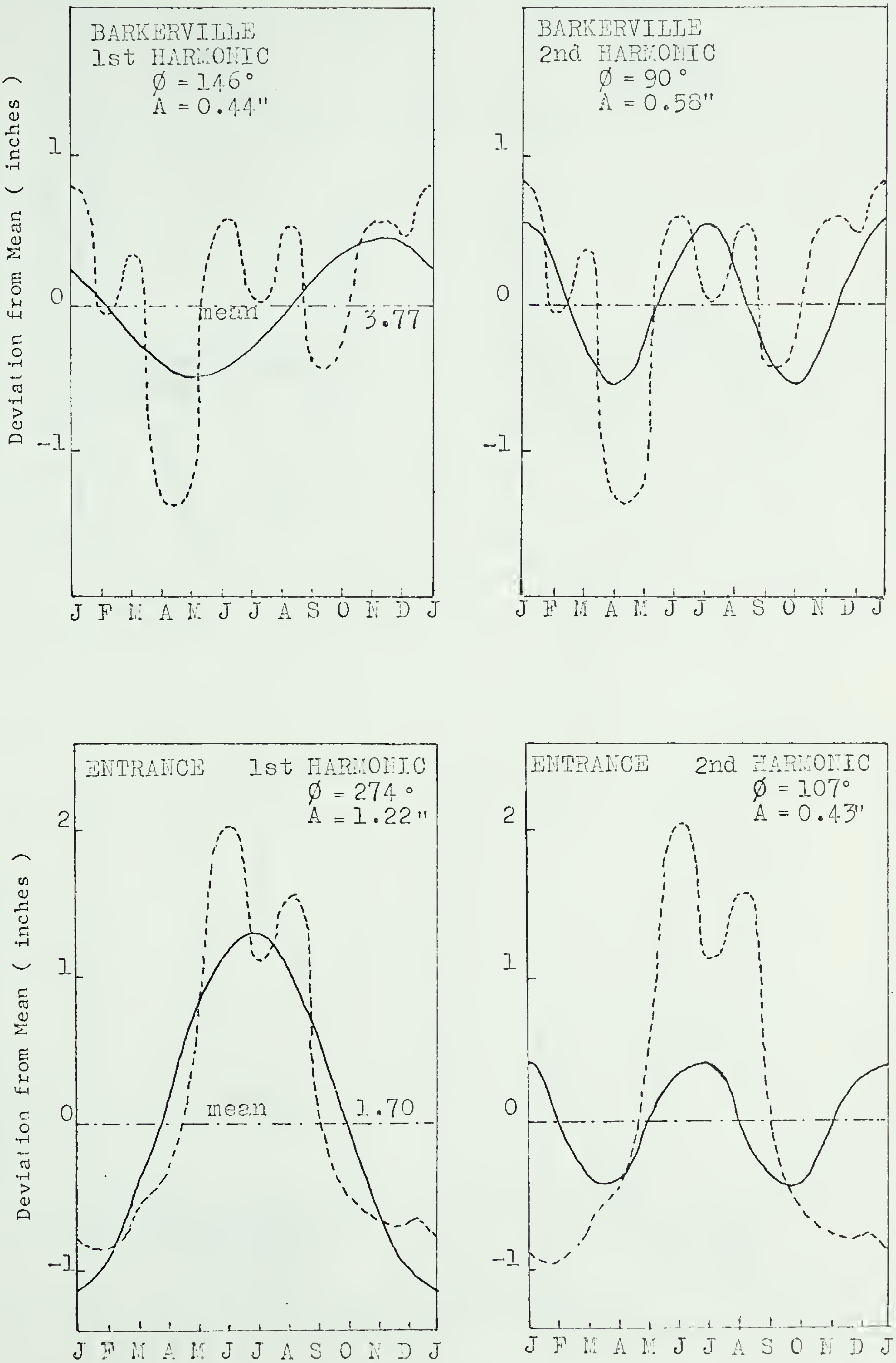
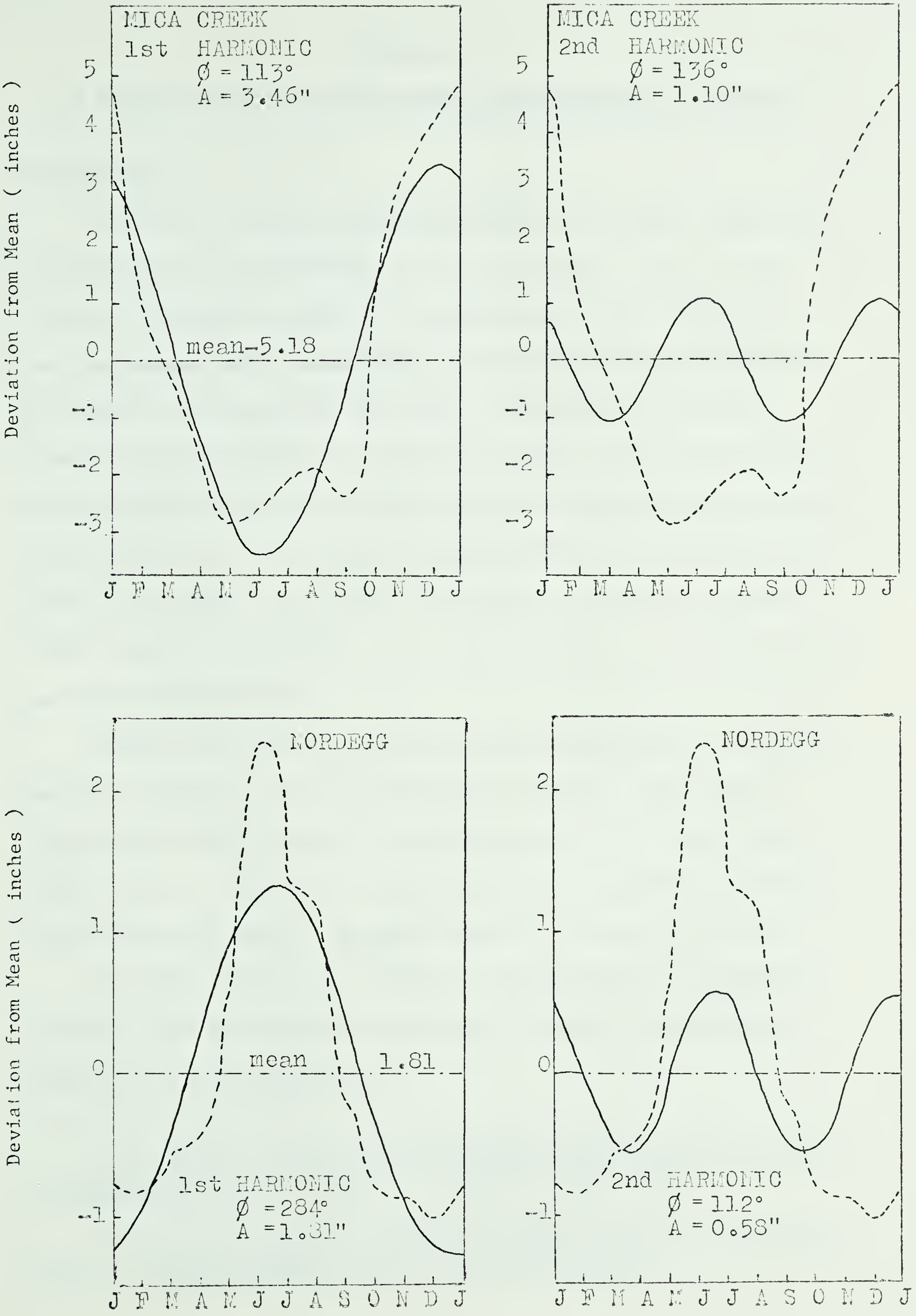

BARKERVILLE
1st HARMONIC
Ø = 146°
A = 0.44"
BARKERVILLE
2nd HARMONIC
Ø = 90°
A = 0.58"
ENTRANCE 1st HARMONIC
Ø = 274°
A = 1.22"
ENTRANCE 2nd HARMONIC
Ø = 107°
A = 0.43"
Deviation from Mean (inches)
mean 3.77
mean 1.70
1
0
-1
2
J F M A M J J A S O N D J

Fig. 3-4


MICA CREEK
1st HARMONIC
Ø = 113°
A = 3.46"
mean-5.18
MICA CREEK
2nd HARMONIC
Ø = 136°
A = 1.10"
Deviation from Mean (inches)
5
4
3
2
1
0
-1
-2
-3
J F M A M J J A S O N D J
NORDEGG
mean 1.81
1st HARMONIC
Ø = 284°
A = 1.31"
NORDEGG
2nd HARMONIC
Ø = 112°
A = 0.58"
2
1
0
-1

Fig, 3-5

CHAPTER IV

AN APPROACH TO QUANTITATIVE MONTHLY PRECIPITATION ESTIMATIONS.

Introduction

Estimates of the precipitation falling on mountain ranges and watersheds are very important to water management, for if we can forecast the probable amount of precipitation, a more effective optimum balance can be established between water storage needs and the risks of overburdening the system. Furthermore, if we can develop a good precipitation model for a given area, we can estimate with a greater degree of confidence the probable precipitation amount. The big problem is to determine the precipitation over barriers and slopes. At present, any effort to estimate or account for precipitation amounts in mountain areas leads inevitably to the formulation and use of simple models.

Myers[1] developed a flow model which incorporated the Bernoulli, the mass continuity, and the hydrostatic formulae. This model, based on an analogy between the atmosphere and the critical depth flow of water, involves the computation of the orographic streamline pattern from atmospheric soundings taken at the foot of the ridge.

It is well known that orographic precipitation is intimately related to the air flow over the barrier. Ideally, precipitation amounts can be determined from[2].

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[1] V.A. Myers, "Airflow in the Windward Side of a Large Ridge". J. Geophys. Res., Vol. 67, No. 11, 1962, pp. 4267-4291.

[2] R.D. Elliott and E.L. Hovind, "The Water Balance of Orographic Clouds". J. Appl. Meteor., Vol. 3, 1964, pp. 235-239.

1. Serial radiosondes and precipitation measurements just upwind of the barrier.
2. Serial radiosondes and precipitation measurements just downwind from the barrier.
3. Precipitation measurements over the barrier itself.

Unfortunately, lack of basic data prevented use of Myers model in this study. Since surface wind data are generally not available for the ridges and slopes of the Rocky Mountains, and the present radiosonde network does not provide sufficient upper air data, it was necessary to develop a workable precipitation model which did not depend on the use of wind observations.

A Simple Precipitation Model

It has been shown in Chapter I that no simple linear relationship exists between elevation, slope and precipitation, for the two groups of stations analysed, west and east of the Rocky Mountains. Thus reporting stations at low elevations, particularly those in a "well", often receive much more precipitation than stations on higher ground and of apparently better exposure.

There is, of course, no good a priori reason for the existence of simple relationships in mountainous regions of such ruggedness and diversity, particularly when many stations are simply "lumped" together, without regard to their individual location. One may ask, however, whether quasi-linear relationships do exist or can be established for small groups of stations in closely similar locations, e.g. in the same valley, and on the same slope of a mountain

range. Lacking an adequate observational network in the study area, this question cannot be answered satisfactorily at present. However, the idea seems attractive enough to warrent at least a preliminary investigation at this time.

Consider an observing station located at a high altitude surrounded by several stations at lower elevations, and assume that this network of stations is adequate to define the distribution and the variation of precipitation with elevation at least within the bounds of this "key" or reference area. Assuming, furthermore, that it is possible to establish simple precipitation-elevation relationships for opposite sides of individual ridges, and precipitation indices for different slopes in a key area, it should be possible also to extrapolate judiciously, and estimate the precipitation on mountain tops and ridges, by the use of derived empirical equations and weighting factors. A weighting factor can usually be derived simply by dividing the number of stations on either the west or east slope of a ridge, by the total number of stations on both sides of the ridge. Using weighted precipitation amounts for mountain tops, and the average precipitation amounts for the sides of a ridge, as well as known differences of elevation, the precipitation indices can be computed for a given ridge. After the indices have been calculated for this ridge, it becomes a reference region whose indices are then applied to a new ridge, in order to estimate its precipitation. By using major ridges as reference regions we can obtain a stepwise solution to the precipitation regime for the area of interest.

The Reference Region

Old Glory Mountain was chosen as the first reference region, since it is the highest station (7,700 feet) with long term precipitation data in British Columbia and Alberta, and good precipitation records are also available for the surrounding stations. Old Glory Mountain is located in southern British Columbia some 230 miles west of the Continental Divide. If we can establish a simple linear relationship between precipitation amount and elevation it could be extended to similar regions close to the reference region. With proper modification, the established relationships could then also be used for slopes and ridges where there are no observations.

Once the precipitation-elevation relationships have been established for a number of reference regions, it should be possible to derive the precipitation pattern in a data-sparse mountainous area with fair accuracy.

Assume a linear relationship of the form:

$$P_H = P_L + C \times DE$$

where P_H and P_L represent average monthly precipitation amounts at the higher (reference) station and lower (surrounding) stations respectively, DE represents the difference in average elevation in thousands of feet between the higher and lower stations, and C is a precipitation index in inches per thousand of feet. In the above equation P_H, P_L and DE are known from the reference regions, consequently C can be computed from the equation. Based on the precipitation indices C found from the reference region, the precipitation

on another mountain can be estimated from the difference in height between the mountain peaks, the average elevation, and the precipitation average of the surrounding stations. In general, mountain ridges in the area of study run from northwest to southeast with deep valleys on both sides where most observing stations are located. Estimated precipitation values for mountain tops vary with the slopes since we are considering mean precipitation amounts on the opposite sides of individual ridges, average elevation for low-lying stations and the variations in the precipitation indices for each slope. As a result, a weighting factor must be adopted in order to obtain the likely precipitation amount for a given mountain top.

A preliminary study of the Old Glory Mountain region showed that almost all the surrounding stations had similar topographical features (see Figure 4-1). In general, they were all located in river basins, with similar elevations and small variations in precipitation amounts. If these stations are grouped into four quadrants, the monthly precipitation amounts averaged, the heights of the stations averaged for each quadrant, and the precipitation indices calculated, little difference is found in C between NW and SW quadrants and NE and SE quadrants. Based on this observation, the stations were further grouped into two sectors depending on whether their slope directions were eastward or westward relative to the reference station (Old Glory Mountain). Stations on the west slope of the reference region include Greenwood, Grand Forks, Deer Park, while the stations located on the east slope are Castlegar, Columbia

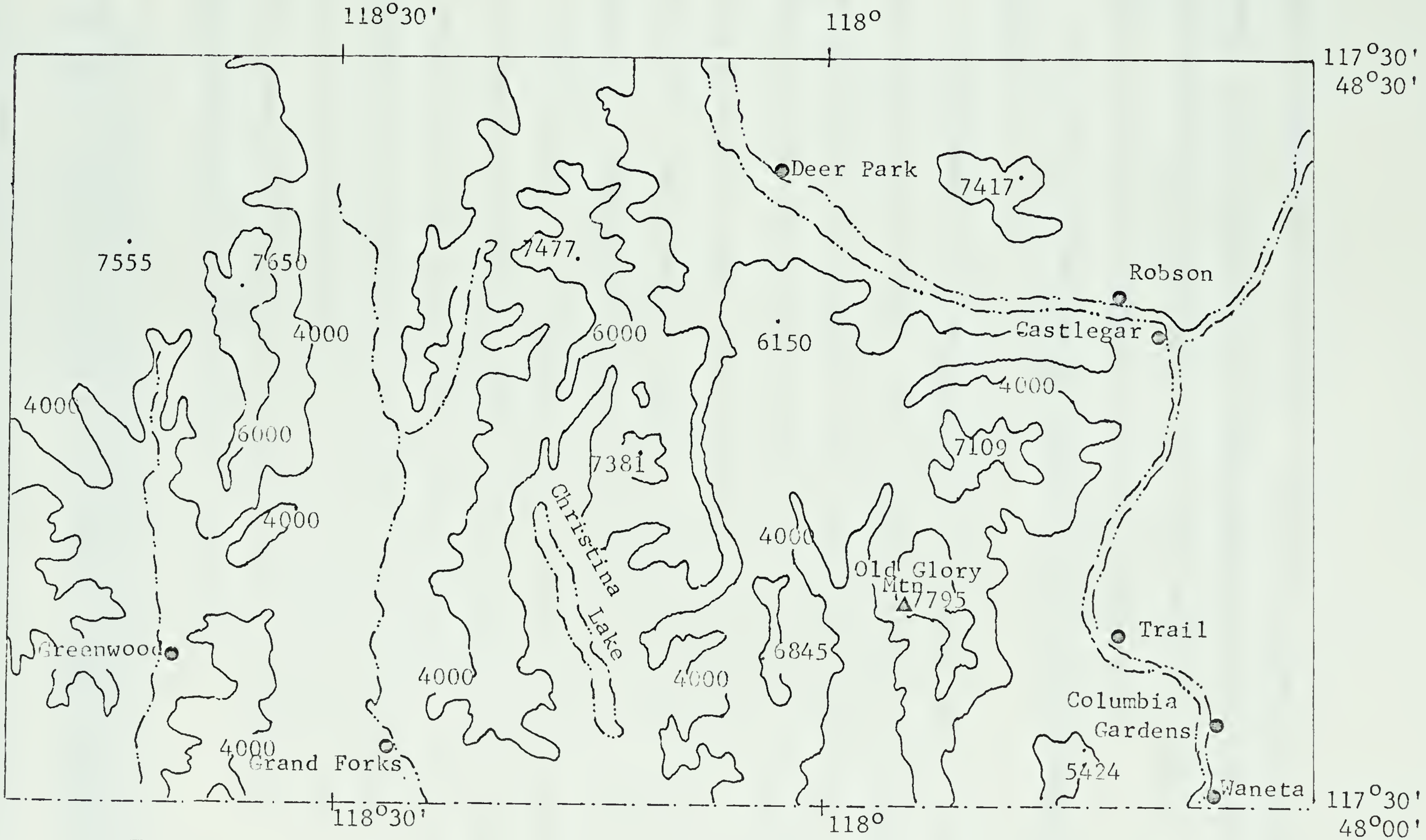

Fig. 4-1 Map showing location of precipitation stations in the Old Glory Mtn region

Gardens, Robson, Trail and Waneta. Table B-1 (Appendix B) shows the average station elevation and average monthly precipitation amounts for all stations on the slopes of Old Glory Mountain. Table B-1 also gives the values of C obtained by the use of equation $P_H = P_L + C \times DE$, and average values for all stations listed in Table B-1.

Unfortunately, the northern part of the study area did not have a high elevation station with precipitation data. Both Mica Creek and Glacier are located in deep "well-like" valleys with elevations of 1,860 and 4,094 feet respectively, and are surrounded by high peaks, with some well in excess of ten thousand feet. In Chapter III it was assumed a station situated in a "well" could be replaced by a fictitious station directly above the real station at a height equal to the average height of the surrounding peaks[3]. This assumption allowed an estimation of the precipitation indices for areas with a lack of stations at high elevations. By a consideration of the average Glacier and Mica Creek precipitation means, and the average elevation of the surrounding peaks, the monthly precipitation values and elevation for the fictitious station were derived. Table B-2 lists these values.

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[3] V.P. Schermerhorn, "Relations Between Topography and Annual Precipitation in Western Oregon and Washington". Water Resources Res., Vol. 3, No. 3, 1967, pp. 707-711.

E.L. Peck and M.J. Brown, "An Approach to the Development of Isohyetal Maps for Mountainous Areas". J. Geophys. Res., Vol. 67, No. 2, 1962, p. 687.

The average height of the mountain peaks for the precipitation zone IV is 10,700 feet. Only two observing stations with relatively long records of precipitation are available: Revelstoke on the west slope of the precipitation zone, and Lake Louise on the east slope. The precipitation indices C for the west slope were obtained from the calculated records for the fictitious station and the actual records for Revelstoke. Using only the values of C obtained from the west slope as input data, an estimate of the precipitation on the mountain top was calculated. Since neither actual station measurement nor calculations based on a fictitious station existed on the east slope, the precipitation amounts on the ridge, estimated from the west slope, were, therefore, used as a weighted mean for this specific precipitation zone. The indices C for the east slope were computed from the weighted mean for the ridge and Lake Louise's actual measurements of east slope precipitation amounts. Table B-2 shows the precipitation indices for both west and east slopes based on this method. The indices, C, for both the east and west slopes, were used as initial values for estimating mountain top precipitation for the next precipitation zone (zone V).

Description of Precipitation Zones

After a consideration of the topography of the study area with special attention given to the location of the principal ridges and the direction of moisture movement, the area was subdivided into northern and southern portions, each containing two or three zones. These zones, shown in Figure 4-2, are designated by Roman Numerals

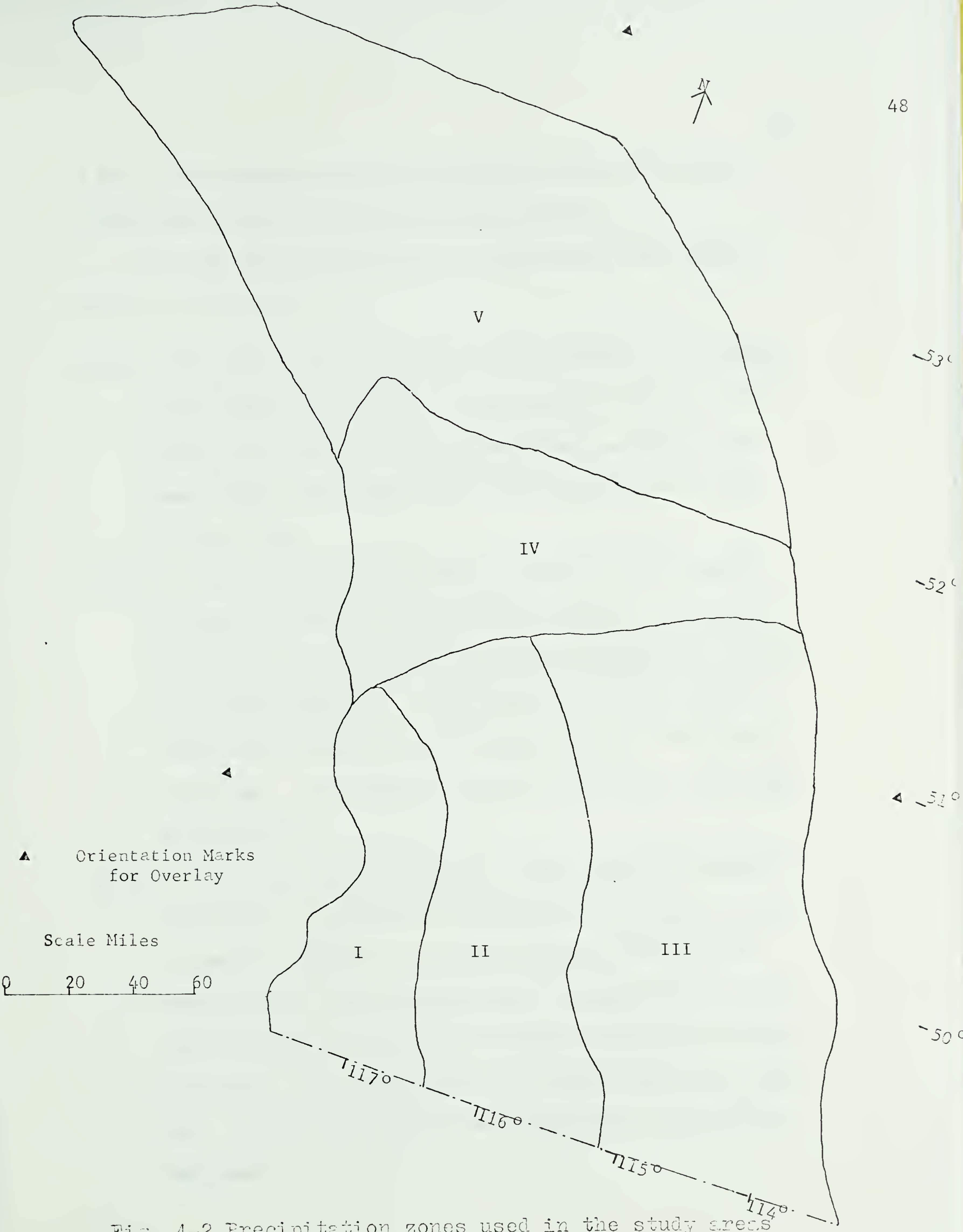

Fig. 4-2 Precipitation zones used in the study areas

I to V. This division allows two reference regions to be used in finding the initial precipitation indices required.

The three precipitation zones in the southern part comprise zones I, II, and III.

Zone I. This zone extends from about 49°N to 50°45'N. It contains a major range, the Selkirks, running north to south. It is bordered on the west by the Columbia River and Slocan Lake. Mount Cooper, the highest peak in this zone has an altitude of 10,135 feet.

Zone II. This zone, stretching from about 49°N to 51°N, includes the Purcell Mountains, running north to south. It is sheltered from the west by the Selkirk range and bordered on the east by the Rocky Mountains. Considering only mountain peaks extending above 10,000 feet, the average height of the peaks is 10,600 feet. Mt. Farnham, elevation 11,378 feet, is the highest in zone II.

Zone III. This zone, stretching from the 49th parallel northward to Lake Louise, includes the interprovincial boundary between the eastern foothills of the Rocky Mountains and the east Kootenay River. The average height of mountain peaks exceeding 10,000 feet in this part of the Rocky Mountains is about 10,700 feet. Mt. Assiniboine is the highest peak with 11,870 feet. In the northern part two precipitation zones were established.

Zone IV. This zone includes part of the Rocky Mountain range, and the extreme northern tip of the Selkirk Mountains. This area is bounded on the west by the Columbia River. Mica Creek and Glacier, having high precipitation records, are used as fictitious stations to estimate the initial precipitation indices for the precipitation zones in the northern part. In zone IV the average height for the mountain peaks is 10,760 feet. Mt. Forbes, the highest peak in this zone rises to 11,852 feet.

Zone V. Zone V comprises the extreme northern part of the study area. It is bounded on the south by zone IV, on the west by the Fraser River, and on the east by the foothills of the Rocky Mountains. Mt. Robson,elevation 12,972 feet, is the highest peak in this zone, as well as in the study area.

Table 4-1 gives all the stations used for analysis in each precipitation zone, the average elevation and precipitation values for these stations are given in Table B-3 (Appendix B).

Table 4-1

Stations Used in Each Precipitation Zone

Precip. Zone	Slope Direction	Station
I	west	Nakusp, New Denver, Castlegar, Robson, Columbia Gardens, Trail, Warfield Trail, Waneta.
	east	Crawford Bay, Kaslo, Wynndel, Creston
II	west	Crawford Bay, Kaslo, Wynndel, Creston
	east	Spillimacheen, Brisco, Ktny. Radium, Canal Flats, Wasa, Kimberley A., Cranbrook A., Wycliffe, Grasmere, Newgate.
III	west	Spillimacheen, Brisco, Ktny. Radium, Canal Flats, Wasa, Kimberley A., Cranbrook A., Wycliffe, Grasmere, Newgate.
	east	Anthracite, Banff, Exshaw, Kananaskis, Pekisko, Coleman, Beaver Mines, Mountain View, Waterton Park, Waterton Park HQ, Lyndon, Waterton L.R. Cabin, Waterton L. Belly R.
IV	west	Revelstoke
	east	Lake Louise
V	west	Red Pass Junction, Cranberry Lake Valemount, Blue River, McBride.
	east	Jasper, Entrance, Nordegg.

Estimation of Precipitation Amount on a Mountain Top

This study made use of two "key" reference regions, the Old Glory Mountain region, and precipitation zone IV. Within zones I, II and III adequate estimates could be derived from observed data, but estimated precipitation amounts for fictitious stations had to be used as data for zone IV and zone V. Thus in the first three zones

precipitation indices were calculated from known values while estimates of indices in zone IV and zone V employed the fictitious station hypothesis.

The following example shows the estimation of precipitation amounts in zone I for January.

(1) Precipitation index $C_W = 0.20$ (Table B-1)

$C_E = -.02$

The working equation is:

$$P_H = P_L + C \times DE \qquad \ldots\ldots (1)$$

where P_H=estimated precipitation on the mountain top

P_L=average precipitation for the lower stations

C= precipitation index

DE=difference in height and P_{HW}, P_{HE}, P_{LE}, P_{LW} , C_W, C_E, DE_W, DE_E, denote respectively, the values for both the west and the east slopes.

From Table B-3 and B-4 we obtain $P_{LW} = 3.25$ and $P_{LE} = 3.18$

$$DE_W = 10.1 - 1.62 = 8.5$$

$$DE_E = 10.1 - 2.01 = 8.1$$

Therefore we obtain the estimated precipitation amount at 10,135 feet to be:

$P_{HW} = 3.25 + 0.20 \times 8.5 = 5.0$ (west slope result)

$P_{HE} = 3.18 - .02 \times 8.1 = 3.0$ (east slope result)

(2) Obviously, the two P_H's are in disagreement. A value of 5.0 inches is obtained using the west slope data while 3.0 inches are obtained with the east slope information. These estimated

precipitation amounts are modified by two weighing factors; 2/3 for the west slope, and 1/3 for the east slope (refer to Table B-5). The adjusted precipitation estimate becomes:

$$P_W = (5.0 \times 2 + 3 \times 1) \div 3 = 4.3$$

(3) After obtaining the adjusted precipitation estimate, the new precipitation indices must be found. These new indices are required to estimate the vertical distribution of precipitation for a particular zone (i.e. zone I) and, more specifically, to estimate the precipitation on the mountain tops of the neighbouring zone. By applying equation 1.

$$C = (P_H - P_L) \div DE \quad \text{we obtain:}$$

$$C_W = (4.3 - 3.25) \div 8.50 = .12$$

$$C_E = (4.3 - 3.18) \div 8.10 = .14$$

(Table B-6)

(4) The precipitation amounts on the mountain top for the adjacent zone were estimated from the precipitation indices for zone I. The results for zone II and zone III, given in Table B-4, were calculated in the following manner:

$$P_{HW} = 3.18 + .12 \times (10.6 - 2.01) = 4.2$$

$$P_{HE} = 1.71 + .14 \times (10.6 - 2.86) = 2.8$$

(Table B-4)

Since no actual data are available from stations on the slopes in the northern region, the fictitious station hypothesis had to be used. From the indices used for zone IV the precipitation amount on the top of zone V was estimated by calculations similar to those for zone II. All the estimated and average values presented in Appendix B were rounded off to two significant figures.

Testing of Results

From the indices given in Table B-6 the precipitation amounts for 7,700 feet (Old Glory Mountain's height) for both the west and the slope were calculated (see Table B-7). Zone I is given as a sample calculation.

$$P_{(W)7,700} = 3.25 + .12 \times (7.7 - 1.62) = 4.0$$

$$P_{(E)7,700} = 3.18 + .14 \times (7.7 - 2.01) = 4.0$$

The precipitation residuals for zone I, II and III were obtained by comparing actual precipitation on Old Glory Mountain and the values calculated for 7,700 feet. Table B-7 gives a list of the precipitation residuals. A precipitation residual is simply the difference between the observed precipitation amount and the estimated value.

Hailstone Butte Lo., Raspberry Lo., Sugarloaf Lo., forestry lookout stations situated in precipitation zone III, and Adams Creek in precipitation zone V on the east slope of the Rockies are operating only in the summer months. The precipitation records from these stations are short and discontinuous. Table 4-2 gives a list of the values used for testing the results. The calculation procedures are exactly the same as mentioned in the preceeding sections. The estimated values and residuals are also given in Table 4-2.

Table 4-2

Summary of Observed and Estimated Precipitation

Station	Precip.(in.)	June *2	July *1	Aug *1	Sept *2	Elevation (ft.)	Years of Rec.
Hailstone	Actual Mean	5.9	2.2	1.8	2.2	7,785	*1 7(61-67)
Butte	Estimate	4.1	2.0	2.4	2.4		*2
Lo.	Residual	-1.8	0.2	0.6	0.2		6(62-67)
	Actual Mean	M	1.4	M	2.0		
Raspberry	Estimate	M	2.0	M	2.4	7,750	5(63-67)
Lo.	Residual	M	0.6	M	0.4		
	Actual Mean	M	M	1.6	M		
Sugarloaf	Estimate	M	M	2.4	M	8,248	7(61-67)
Lo.	Residual	M	M	0.8	M		
Adams	Actual Mean	2.3	4.1	M	M		
Creek	Estimate	3.1	3.1	M	M	7,250	6(62-67)
Lo.	Residual	0.8	-1.0	M	M		

Source: Monthly Records. M: Records are discontinuous and short. Minus sign indicates that the estimated value is less than the actual value.

Table 4-3

Summary of Grand Mean and Estimated Precipitation

Average Elevation(ft.)	Precipitation (in.)			
7,930	June	July	Aug	Sept
Grand Mean	5.9	1.8	1.7	2.1
Estimate (in.)	4.1	2.0	2.4	2.4
Residual (in.)	-1.8	0.2	0.7	0.3

Discussion

If the initial precipitation indices obtained from the Old Glory Mountain region are applied to the precipitation zones I, II and III, both the precipitation amounts on the ridges and the new precipitation indices for each zone can be estimated. The values

obtained from these estimates show minor deviations from the values listed in Appendix B.

By applying the precipitation indices for zone III to zone IV, the precipitation on the mountain tops and the new indices for zone IV can be estimated. The estimated zone IV indices were applied to zone V to obtain a new set of precipitation indices which subsequently produced an estimate of the precipitation at 7,250 feet (Adams Creek Lo.). Comparing these results with the observed values in Table 4-2, they are less accurate than the results listed in Table 4-2.

The "fictitious station" hypothesis used in this chapter yields adequate results within certain limits. The residual for the Adams Creek in June was 0.8 inches but increased to 1.1 inches for July. These correspond to approximate percentage errors of 36% and 25% for June and July respectively.

The residuals for Hailstone Butte Lo., Raspberry Lo., Sugarloaf Lo., lookout stations as listed in Table 4-2 are relatively high due to the brevity of and discontinuities in their precipitation records. Hailstone Butte Lo., for example, received 13.10 inches of precipitation in June 1963 but only 2.50 inches in June 1962. The 1963 record plays a major role in the high average obtained for the 1962-1967 period. If we compare the grand average values for these three stations with the estimated value as listed in Table 4-3, the residuals decrease. Since the precipitation amounts on the mountain tops were estimated by utilizing the average values for the lower stations, the average results seem more reliable than the results

obtained for individual stations.

The precipitation model developed assumes the existence of linear relationships between elevation and precipitation, consequently the rate of precipitation increase or decrease with elevation is uniform. Such relationships may hold for certain ranges of height only and for individual months, depending on the meteorological and physiographic features of the particular region of the study area. In certain months and at certain heights, the precipitation may increase for the first few thousand feet, at a varying rate, and then decrease again higher up.

It is not possible at present to establish the precipitation pattern of the Rocky Mountain's uniquely or even adequately. The simple precipitation model used in this study is obviously incapable of dealing with a system of such great complexity, and the results presented here are, therefore, in no way intended to be conclusive or final. Even so, it appears safe to say that the precipitation estimates derived from this simple model are appreciably better than pure guesswork. Future studies based on more and longer records should make it possible to fill in the gaps, and produce better estimates for the remote and inaccessible regions. In the meantime, it is hoped that these tentative results will be found useful as a first approximation solution of a complicated problem.

CHAPTER V

PRECIPITATION PROFILES

Precipitation Profiles

In Chapter IV a quasi-linear relationship was assumed to exist between precipitation and elevation, in order to derive practical indices of precipitation distribution. These indices were used to construct two precipitation profiles of the study area, along the 49th and 50th parallels. Cross sections of the terrain were drawn from data abstracted from the maps published by Canada, Surveys and Mapping Branch, Department of Mines and Technical Surveys[1].

Atlases and various other books display precipitation profiles which generally follow the contours of the terrain, rising over mountain peaks and falling over the valleys. This is obviously an oversimplification, resulting largely from a lack of data, for the converse may in fact be true, at least in certain months, or with stations in a "well".

A sufficient distribution of stations with reliable records is essential if accurate precipitation profiles are to be constructed. Stations located at or close to the critical positions of profile extremes - mountain peaks and valley bottoms - are especially useful, but only rarely available. Drawing a profile without such "anchor" points is difficult and subject to larger errors.

It is necessary also that the stations used are representative

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[1] The terrain profiles were provided by E.R. Reinelt. Scale 1:250,000; Contour interval 500 feet.

of the region, and not too far from the true line of the profile. In the present case, the reporting stations are located mostly in valleys and river basins, but never more than 15 minutes of latitude or about 18 miles from the true line of the terrain profile. It may be assumed, therefore, that the precipitation data used are typical and representative of the conditions along the actual profile.

Procedure for Drawing the Profiles

Since no recording stations exist on the crests of the high ridges in the study area, precipitation amounts on the peaks were estimated from the actual records of the nearest relevant stations and the equation $P_H = P_L + C \times DE$. In cases where precipitation amounts estimated from the west and east sides of a ridge were different, the representative value was assumed to equal the mean of the two estimates.

Precipitation profiles for the cold months (December, January, February) and the warm months (June, July, August) were drawn in order to compare the seasonal extremes. The three-month precipitation totals and the precipitation indices for each station were obtained by summing the monthly precipitation amounts and the precipitation indices, respectively, for the stations used, over the three-month periods. The annual precipitation profile was drawn up from the precipitation amounts and precipitation indices summed over twelve months. The topographical and precipitation profiles were drawn separately. The station locations were plotted along the abscissa, but only the station numbers were given. Tables 5-1 and

5-2 list the stations used in these profiles. The precipitation profiles for the cold months, warm months and the total annual precipitation are shown in Figures 5-1 to 5-6.

The profile along the forty-ninth parallel extends over about 250 miles and includes 16 reporting stations; the profile for the fiftieth parallel covers about 170 miles and includes six stations. The average linear station density is thus one station per 16 miles and 28 miles, respectively, for the profiles along the forty-ninth and the fiftieth parallel. However, since reporting stations are concentrated in the valleys and foothills, the distribution is far from being uniform.

These profiles are intended to be only a first approximation to the precipitation distribution in Southwestern Alberta and Southeastern British Columbia. Since precipitation amounts for certain months decrease with elevation, the precipitation curves do not necessarily follow the patterns of the terrain cross-section. More observational data and further studies are necessary to refine these precipitation profiles.

Table 5-1

Stations Used for the 49th Profile

Sta. No.	Station Name	Lat. (deg.min.)	Long. (deg.min.)	Elev. (ft.)	Precip. Total (inches)		
					Cold months	Warm months	Annual
1	Carway	49.00	113.22	4,460	3.62	6.68	20.37
2	Mountain View	49.08	113.38	4,325	4.29	6.69	22.56
3	Waterton Lakes Belly R.	49.03	113.42	4,500	9.01	9.90	39.06
4	Waterton Park	49.07	113.44	4,300	6.01	6.50	26.18
5	Waterton Lakes R. Cabin	49.07	113.51	4,200	8.95	8.71	35.76
6	Waterton Park HQ	49.03	113.55	4,200	12.03	9.01	42.31
7	Grasmere	49.06	115.05	2,850	3.94	6.50	18.34
8	Newgate	49.01	115.09	2,325	4.84	3.39	15.03
9	Creston	49.06	116.31	2,085	6.65	3.65	18.94
10	Wynndel	49.11	116.33	2,025	7.64	4.21	23.40
11	Waneta	49.01	117.35	1,880	8.12	4.61	24.02
12	Columbia Gardens	49.03	117.36	1,420	8.52	4.60	24.90
13	Warfield Trail	49.06	117.44	1,987	9.83	4.58	26.91
14	Old Glory Mtn.	49.09	117.55	7,700	8.74	6.62	29.52
15	Grand Forks	49.02	118.27	1,746	5.45	3.71	17.13
16	Greenwood	49.05	118.41	2,490	4.60	4.43	17.12

Table 5-2

Stations Used for the 50th Profile

Sta. No.	Station Name	Lat. (deg.min.)	Long. (deg.min.)	Elev. (ft.)	Precip. Total (inches)		
					Cold months	Warm months	Annual
1	New Denver	49.59	117.23	1,850	10.44	5.57	29.79
2	Kaslo	49.55	116.55	1,930	11.60	5.11	29.77
3	Canal Flats	50.09	115.54	2,680	4.41	4.72	16.20
4	Wasa	49.49	115.38	3,050	3.84	4.00	14.57
5	Lyndon	50.01	113.53	4,100	2.79	7.78	20.11
6	Claresholm	49.56	113.45	3,450	2.60	5.54	15.70

Fig. 5-1 Annual Precipitation Profile along Forty-Ninth Parallel

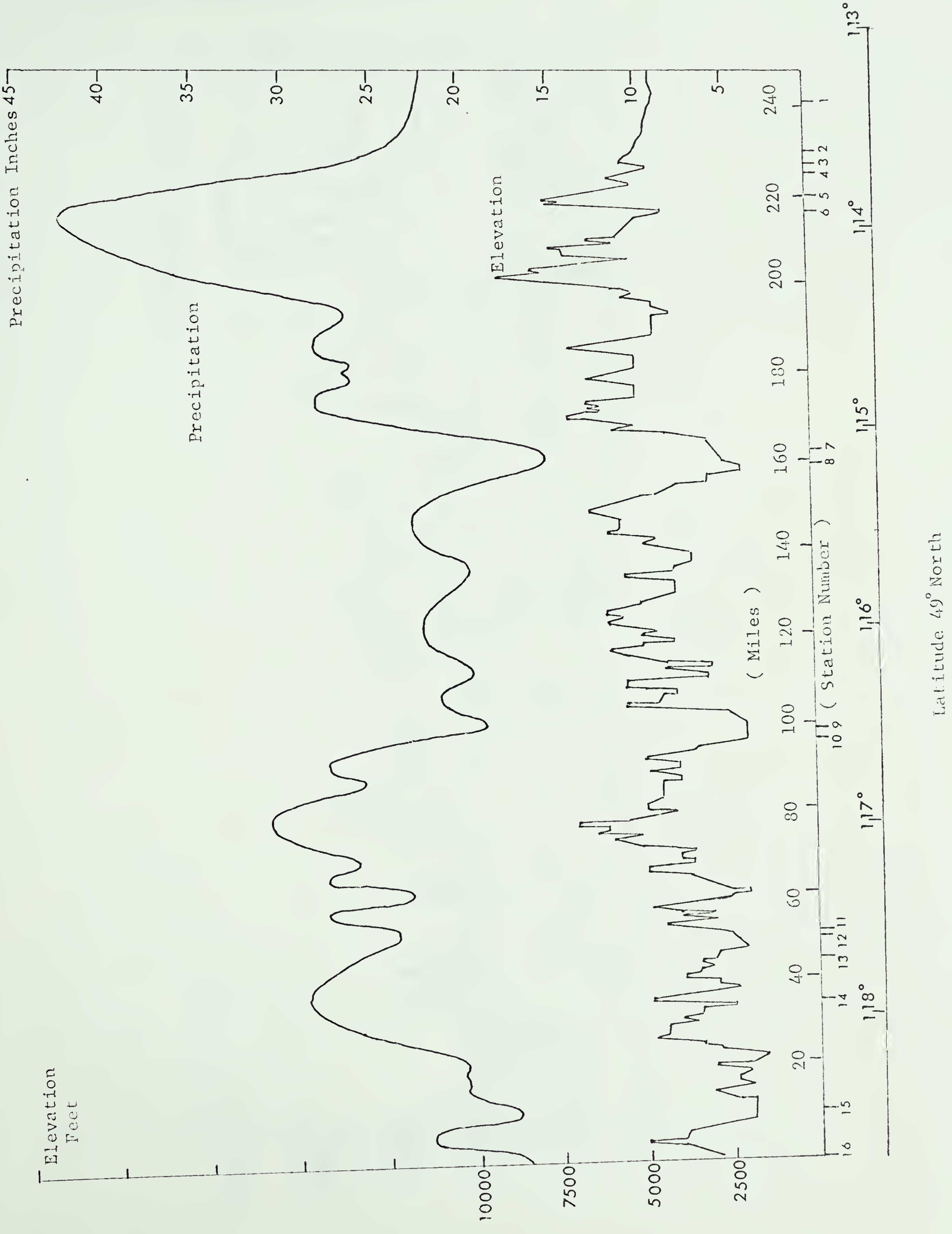


Fig. 5-2 Warm months (June, July, Aug.) Precipitation Profile along Forty-Ninth Parallel

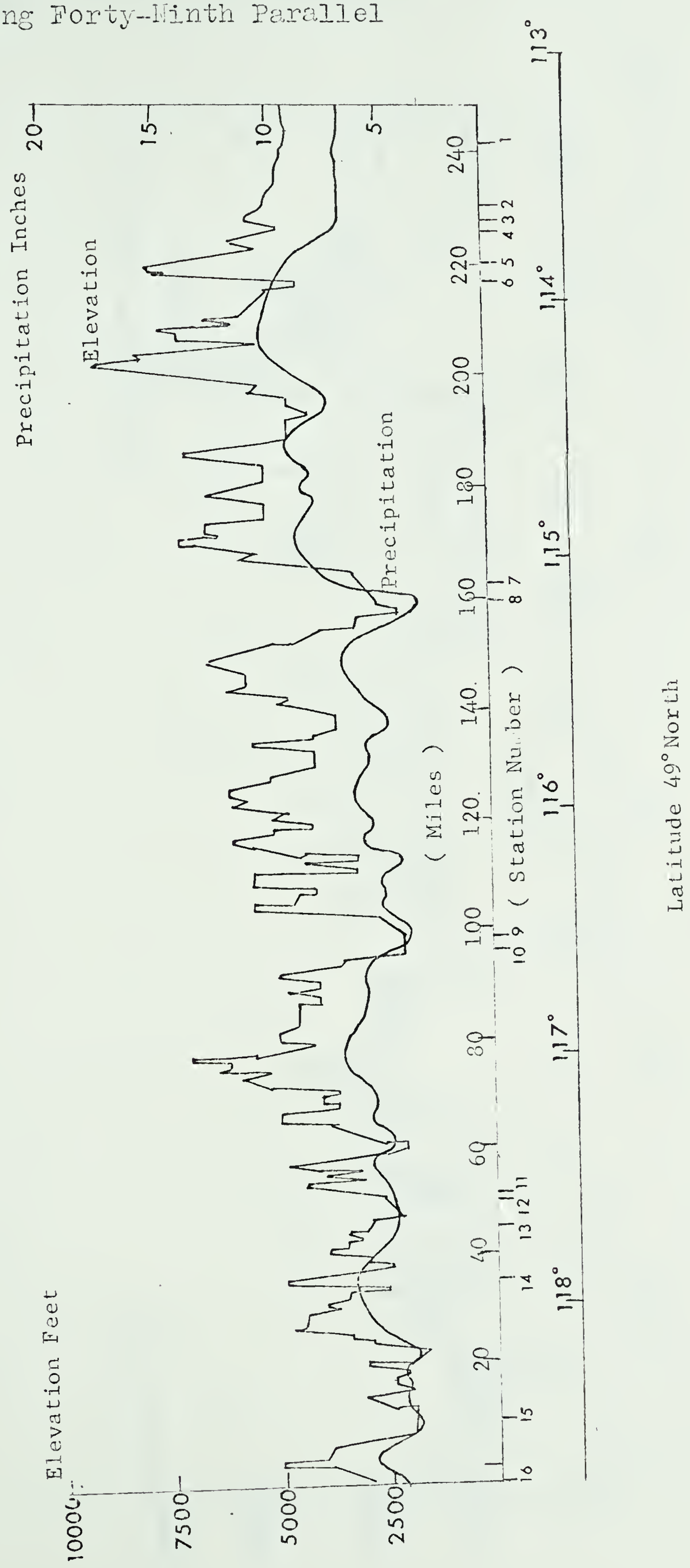


Fig. 5-3 Cold months (Dec. Jan. Feb.) Precipitation Profile along Forty-Ninth Parallel

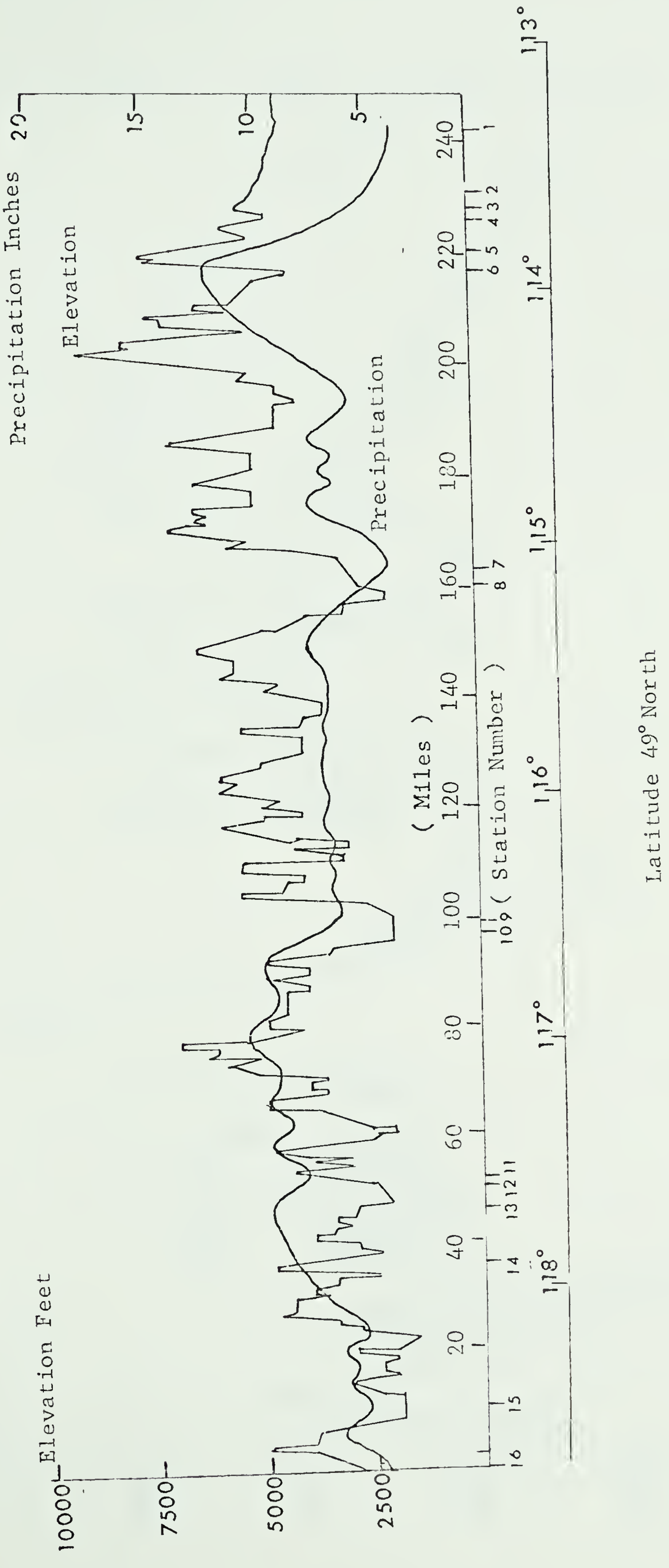


Fig. 5-4 Annual Precipitation Profile along Fiftieth Parallel

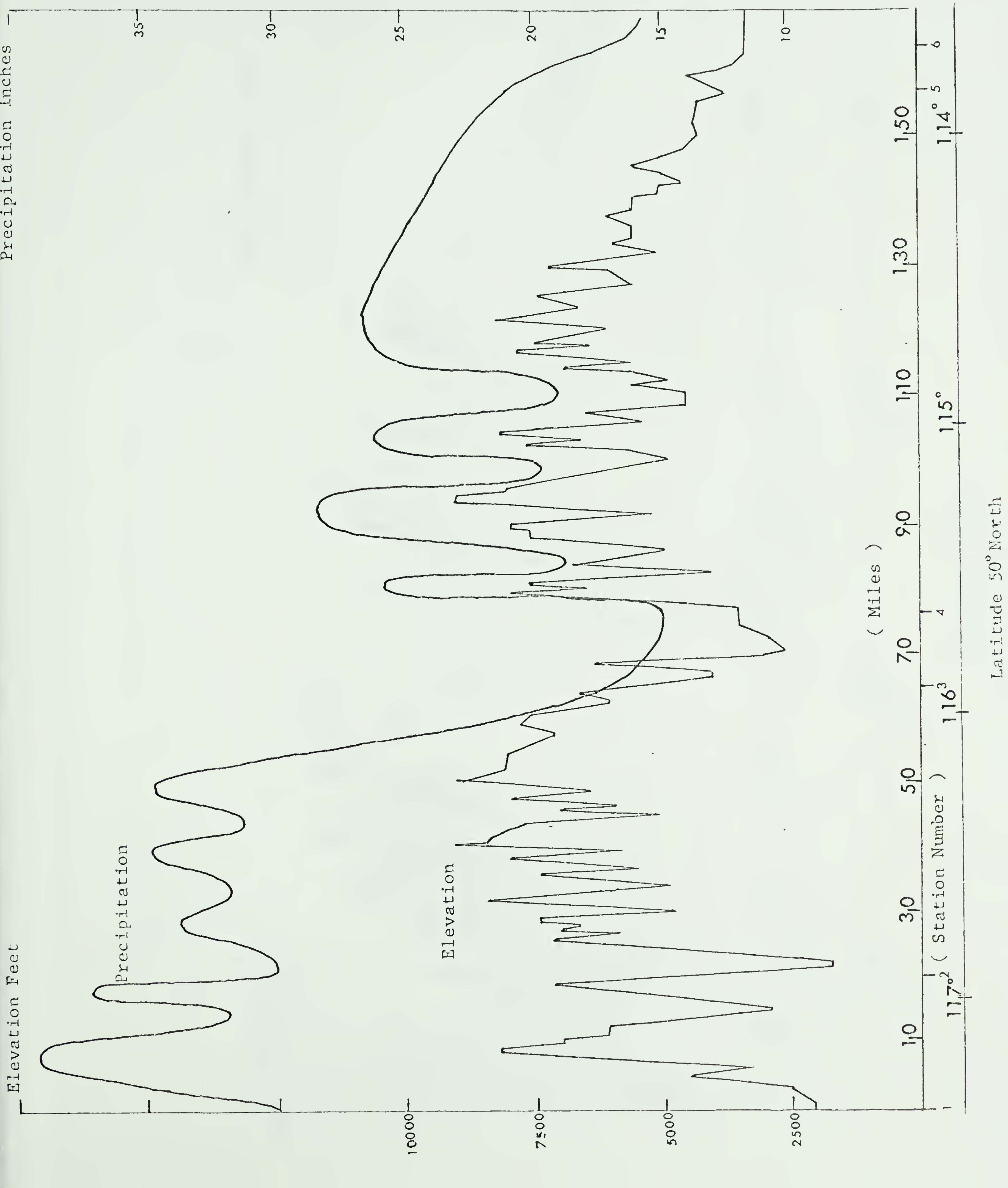


Fig. 5-5 Warm months (June, July, Aug.) Precipitation Profile along Fiftieth Parallel

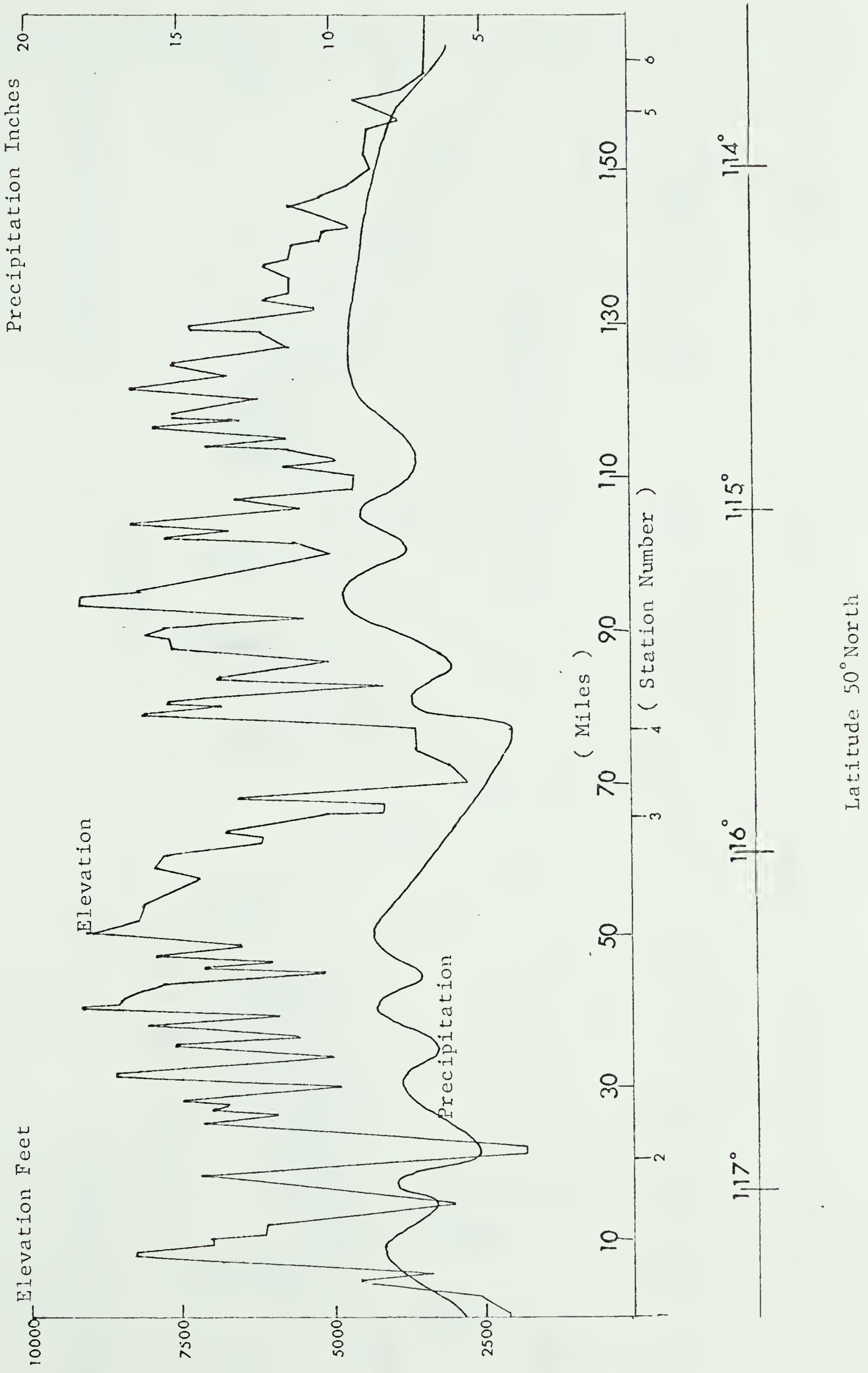
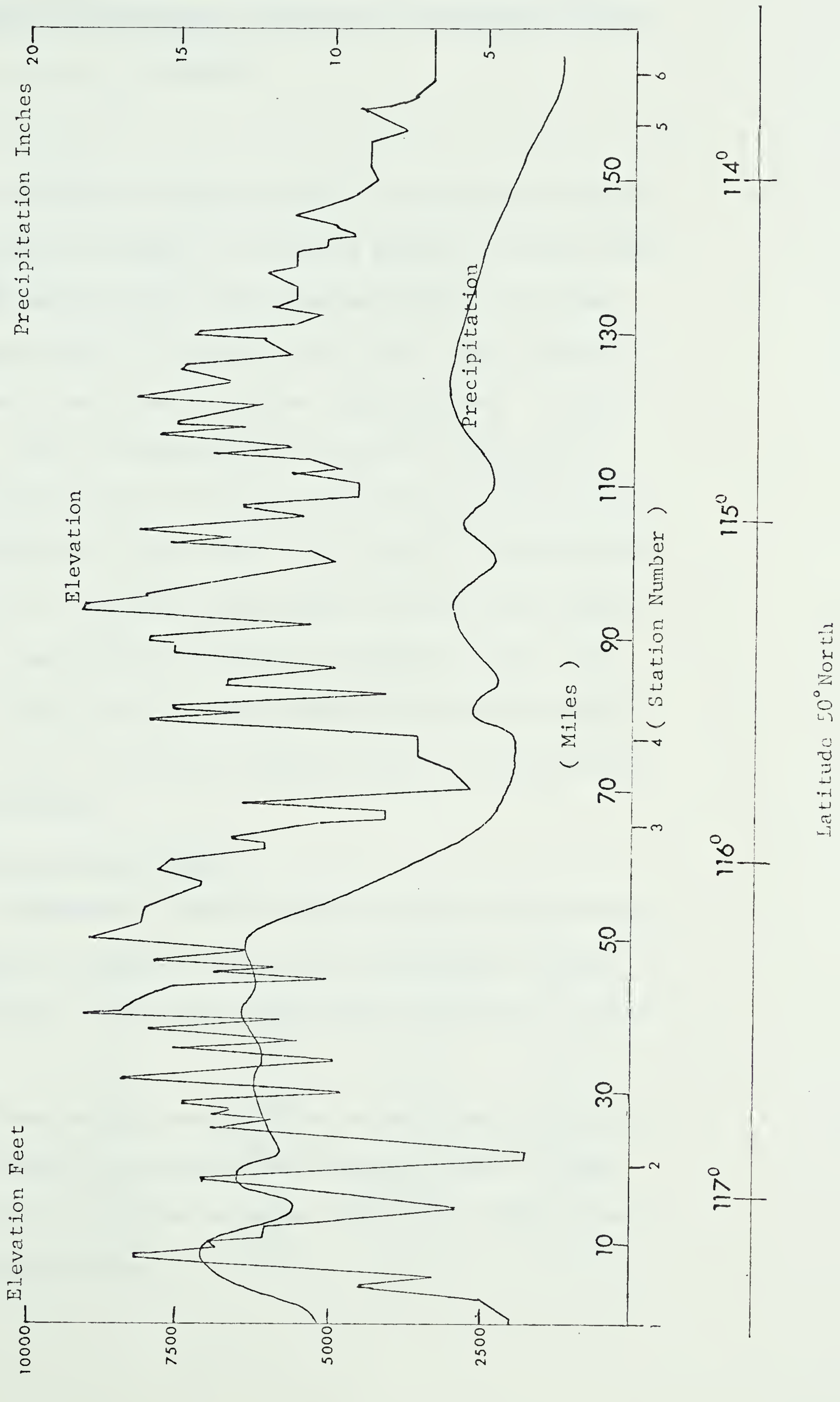


Fig. 5-6 Cold months (Dec. Jan. Feb.) Precipitation Profile along Fiftieth Parallel



CHAPTER VI

PRECIPITATION MAPS OF SOUTHWESTERN ALBERTA AND SOUTHEASTERN BRITISH COLUMBIA.

Introduction

The lack of detailed isohyetal maps of the mountainous regions of Alberta and British Columbia is a serious problem to anyone interested in the hydrometeorology of the Canadian Rockies. What few precipitation maps exist of this area are of small scale, and too generalized to be of much use in serious investigations. It was felt, therefore, that an attempt should be made at this time to produce a more detailed set of isohyetal maps for the five precipitation zones considered in this study. The dearth of observational data, and the use by necessity of too simple a precipitation model again rules out construction of definitive isohyetal maps. Even so, it is hoped that the set of maps produced under such stringent limitations will still be accurate enough to serve a useful purpose in future investigations.

Construction of the Isohyetal Maps

Sectional aeronautical charts, scale 1: 100,000, published by the Canada Survey and Mapping Branch, were used as base maps for the isohyetal charts. The isohyets were drawn on the basis of the following:

1. The actual monthly precipitation at each observing station.
2. The average precipitation and elevation (refer to Table B-3) for all stations on either side of the ridge in each precipitation zone.

3. The quasi-linear precipitation-elevation relationship assumed in Chapter IV.

Precipitation amounts on the ridges are based on the data listed in Table B-5. A variable isohyet interval was chosen for different precipitation zones since estimated precipitation amounts on the slopes and on the ridges were subject to large variations from month to month. An interval of 0.5 inches was chosen as the basic interval between adjacent isohyets for monthly precipitation maps.

The annual precipitation map was constructed by summing the mean monthly precipitation amounts for the stations on both the east and the west slopes for each precipitation zone (refer to Table B-3). The annual precipitation indices for west and east slopes in each zone were found by summing the individual monthly precipitation indices. In drawing the annual map, observed precipitation amounts of each station were also taken into account. Table 6-1 gives the data used in preparing the annual map.

Table 6-1

Annual Precipitation Summary

Precip. Zone	Average Elev. of Peaks (Thousands of ft.)	Estimated Annual Total (in.)	Slope Direction	Precip. Index C (in./1,000ft.)	Sum of the Monthly Means (in.)
I	10.1	40.1	west	1.57	26.77
			east	1.75	25.81
II	10.6	32.8	west	0.83	25.81
			east	2.05	16.95
III	10.7	31.8	west	1.89	16.95
			east	0.94	25.96
IV	10.7	61.5	west	2.08	42.54
			east	5.42	30.37
V	11.1	50.6	west	2.83	26.85
			east	4.31	19.24

Difficulties in Constructing Isohyets

Based on meteorological and physiographic features, the study area was divided into five precipitation zones. Since these zones cover large areas of rugged terrain, abrupt changes occur in the precipitation-elevation relationships along the borders of adjacent zones. Thus differences in the correlations produce discontinuities and uncertainties in the isohyets along the borders. This effect is especially evident along the borders of zone IV, where the precipitation amounts were estimated on the basis of the "fictitious station" hypothesis. The precipitation amounts on the ridges were significantly different in the winter months from the amounts obtained for zones I, II and III. During January, for example, the weighted means on the ridge for zones III and IV were 2.4 inches and 9.1 inches respectively (refer to Table B-5). Isohyets in zone IV crossing into zone III correspond to values of precipitation exceeding the amounts estimated for places in zone III. However, since the distribution of precipitation must be continuous, the discontinuities were removed by smoothing and judicious averaging.

Discussion

Throughout the summer months (April - September) the precipitation patterns show remarkable uniformity of structure and amounts. During the winter months the precipitation increases in zone IV and in the areas adjacent to Waterton Lakes. There are considerable variations in precipitation from winter to summer, with the heaviest

precipitation in zone IV.

The assumption that precipitation increases with elevation seems to be valid for most months except in a few cases where the indices were negative. Since the annual precipitation indices are always positive, the annual precipitation amounts are on the whole directly proportional to elevation. It will be necessary to obtain many more precipitation records for the slopes and ridges before more satisfactory relationships can be established. The results obtained by using linear relationships could probably be refined to some degree by using smaller and more uniform precipitation zones, but the low reporting station density would seem to rule out much improvement at the present time.

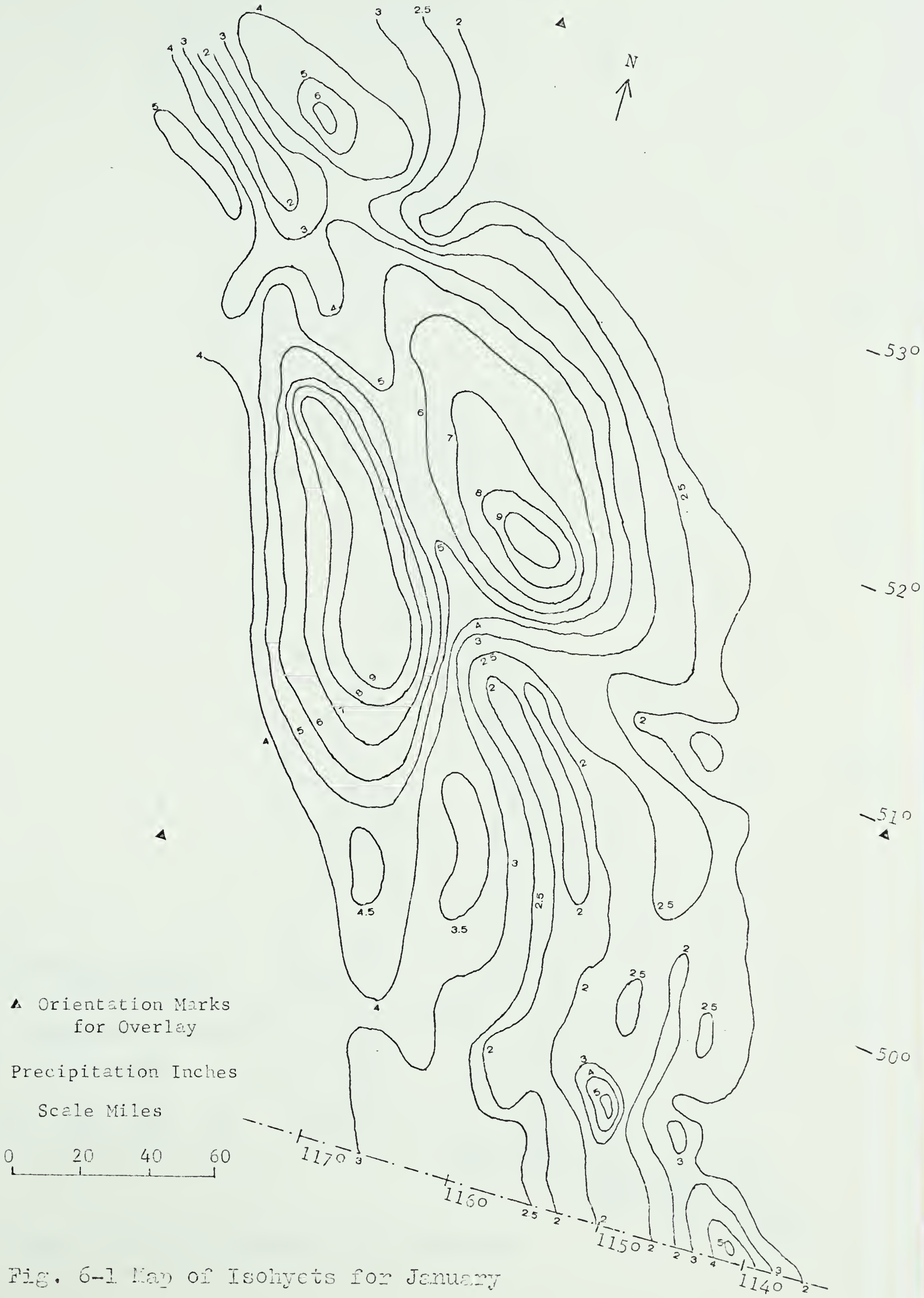


Fig. 6-1 Map of Isohyets for January

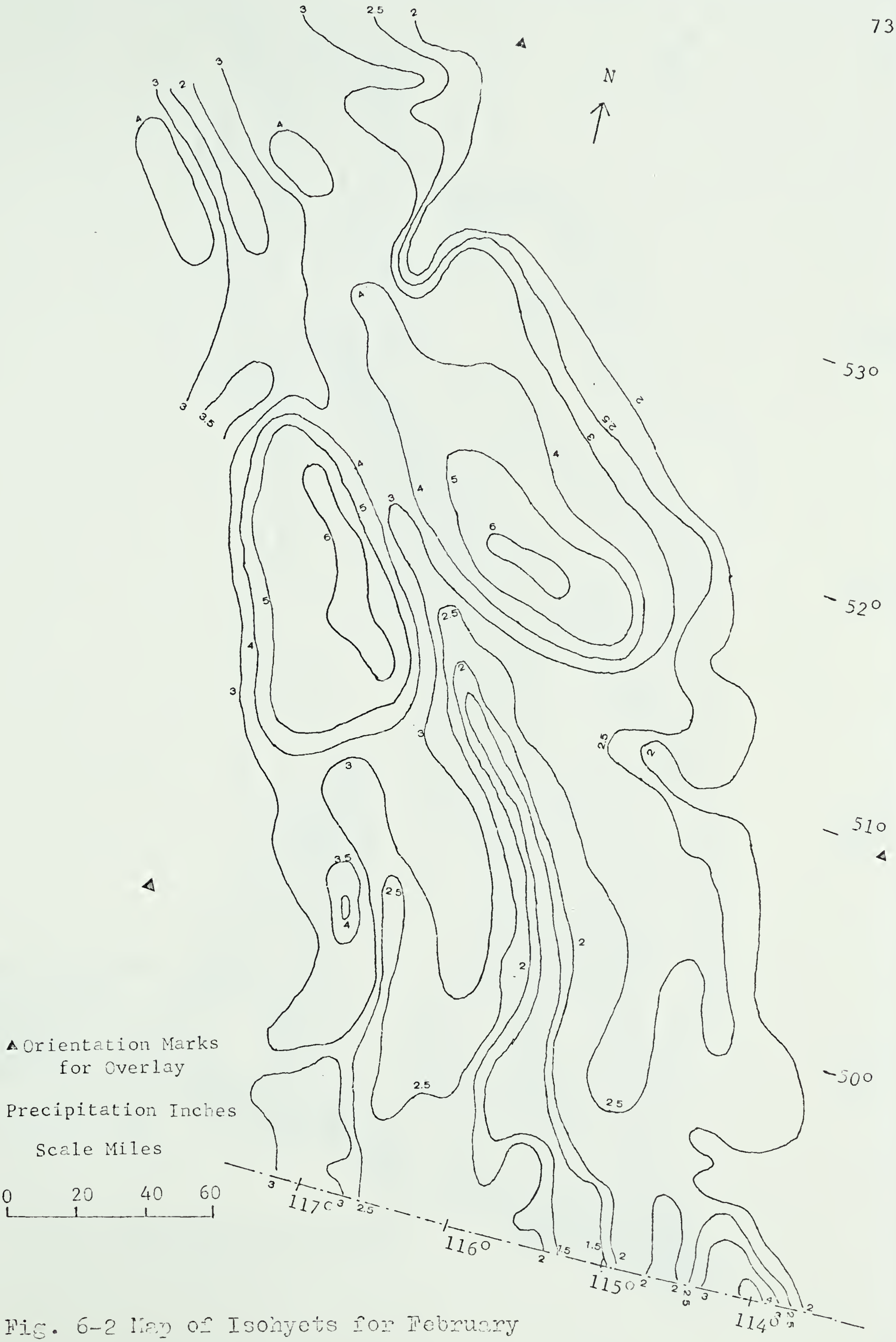


Fig. 6-2 Map of Isohyets for February

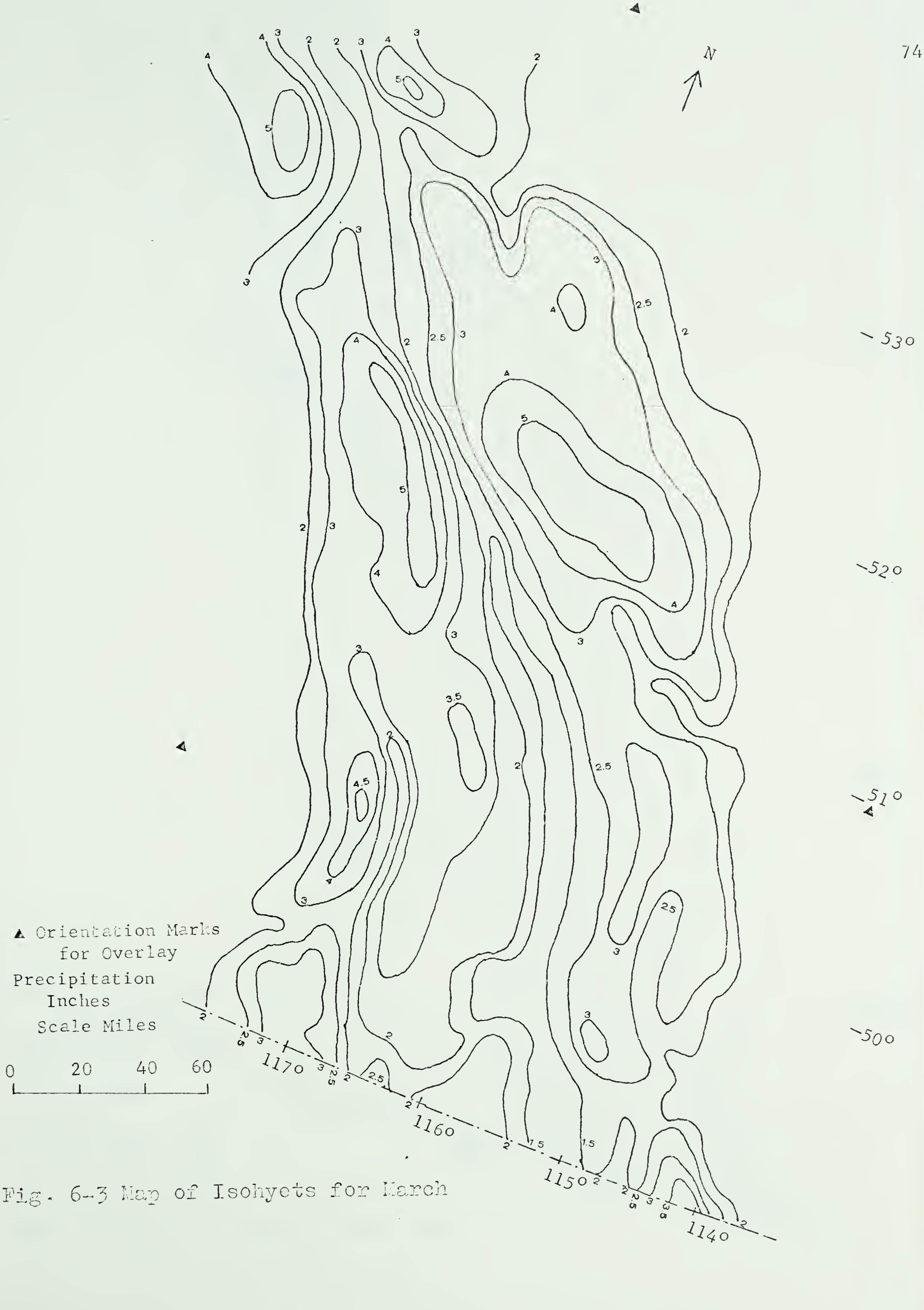


Fig. 6-3 Map of Isohyets for March

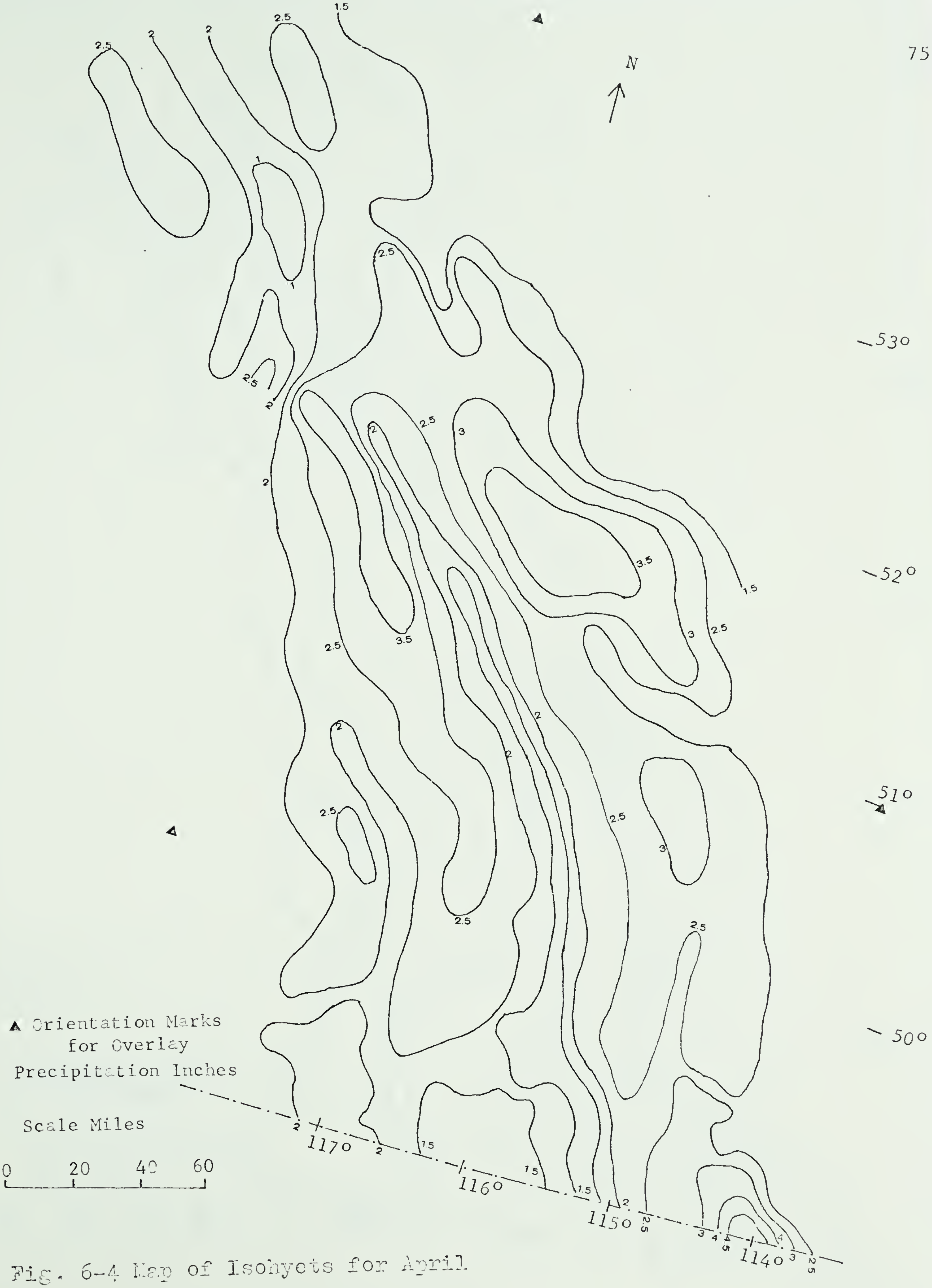


Fig. 6-4 Map of Isohyets for April

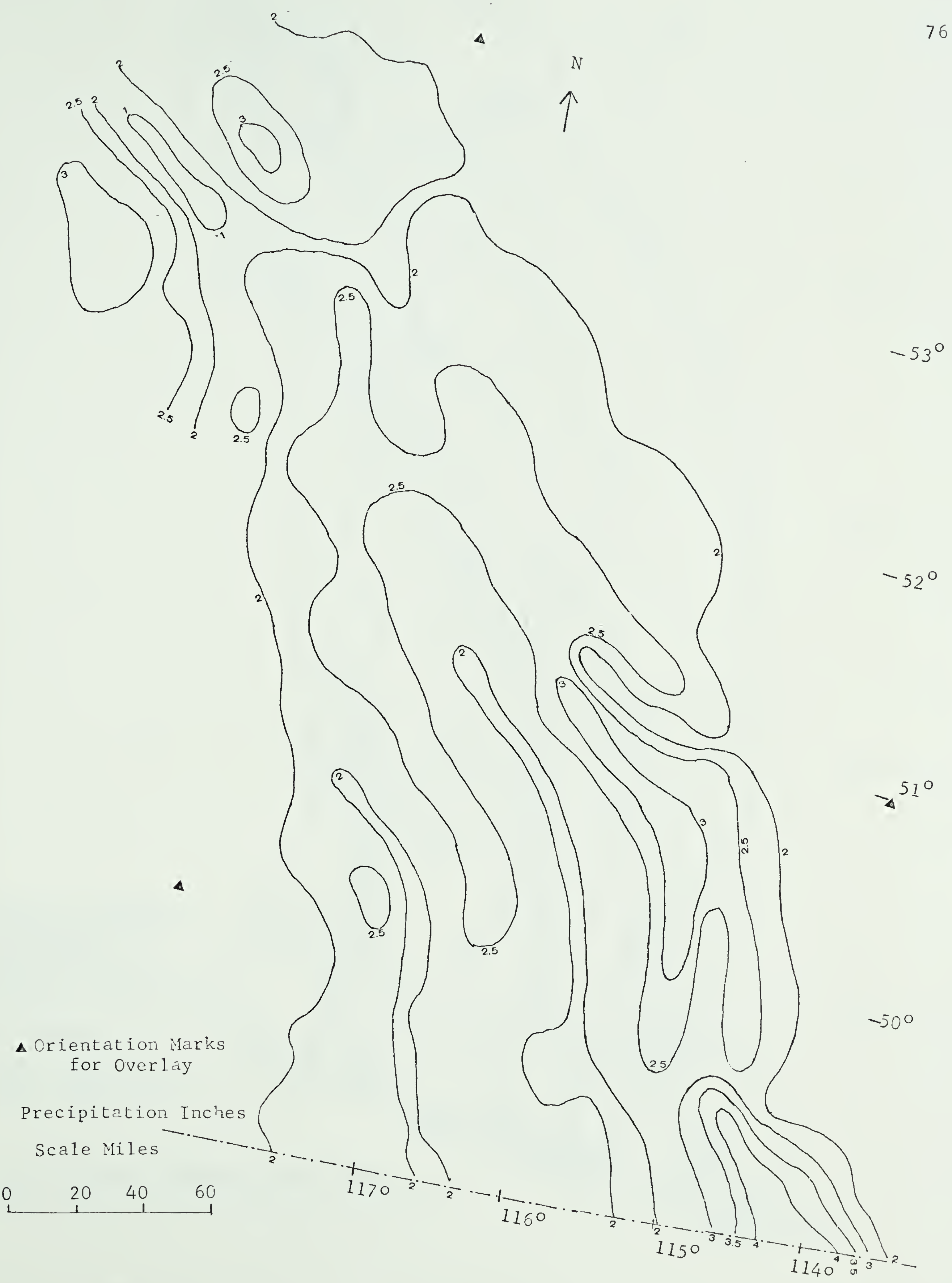


Fig.6-5 Map of Isohyets for May

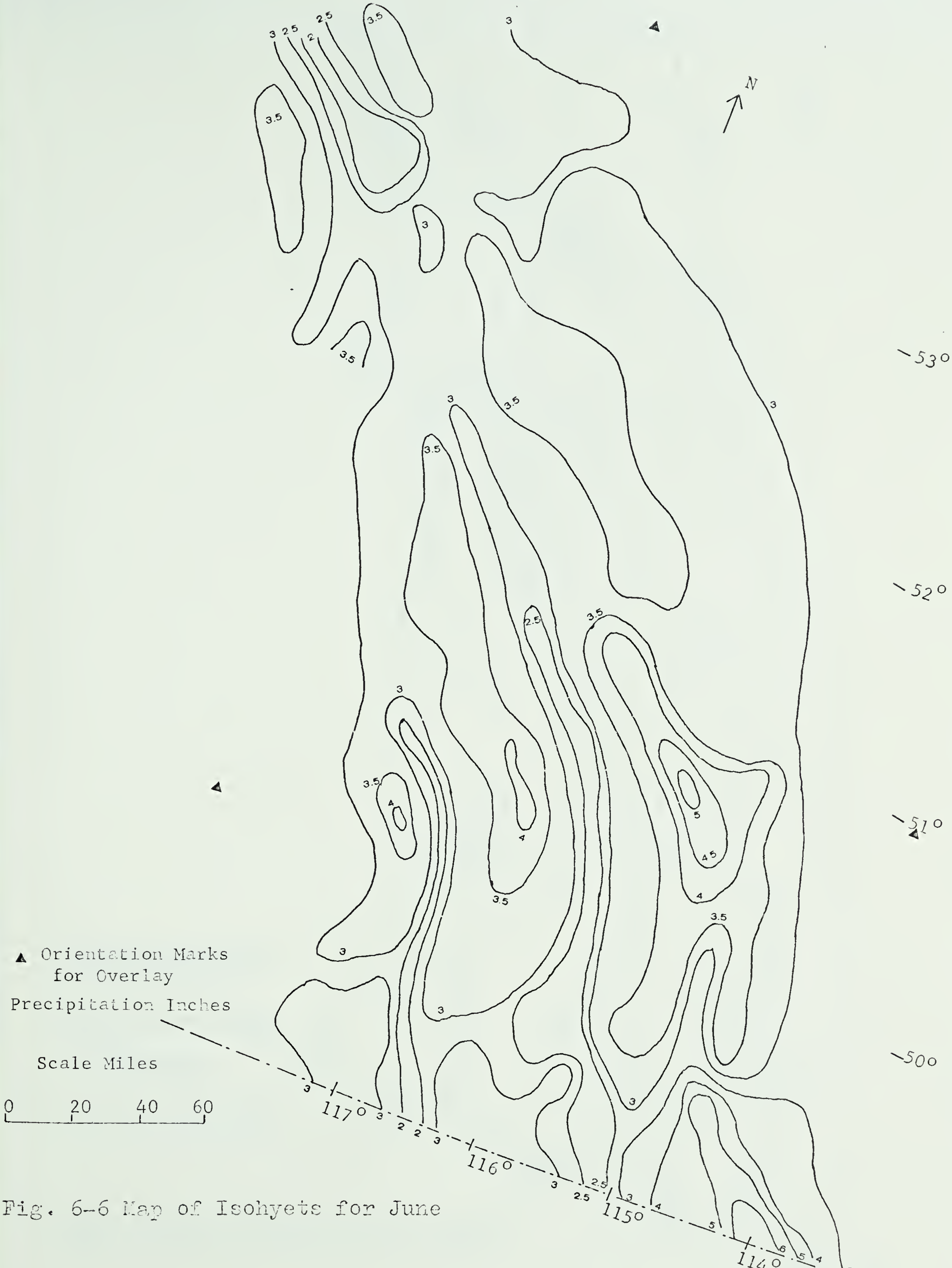


Fig. 6-6 Map of Isohyets for June

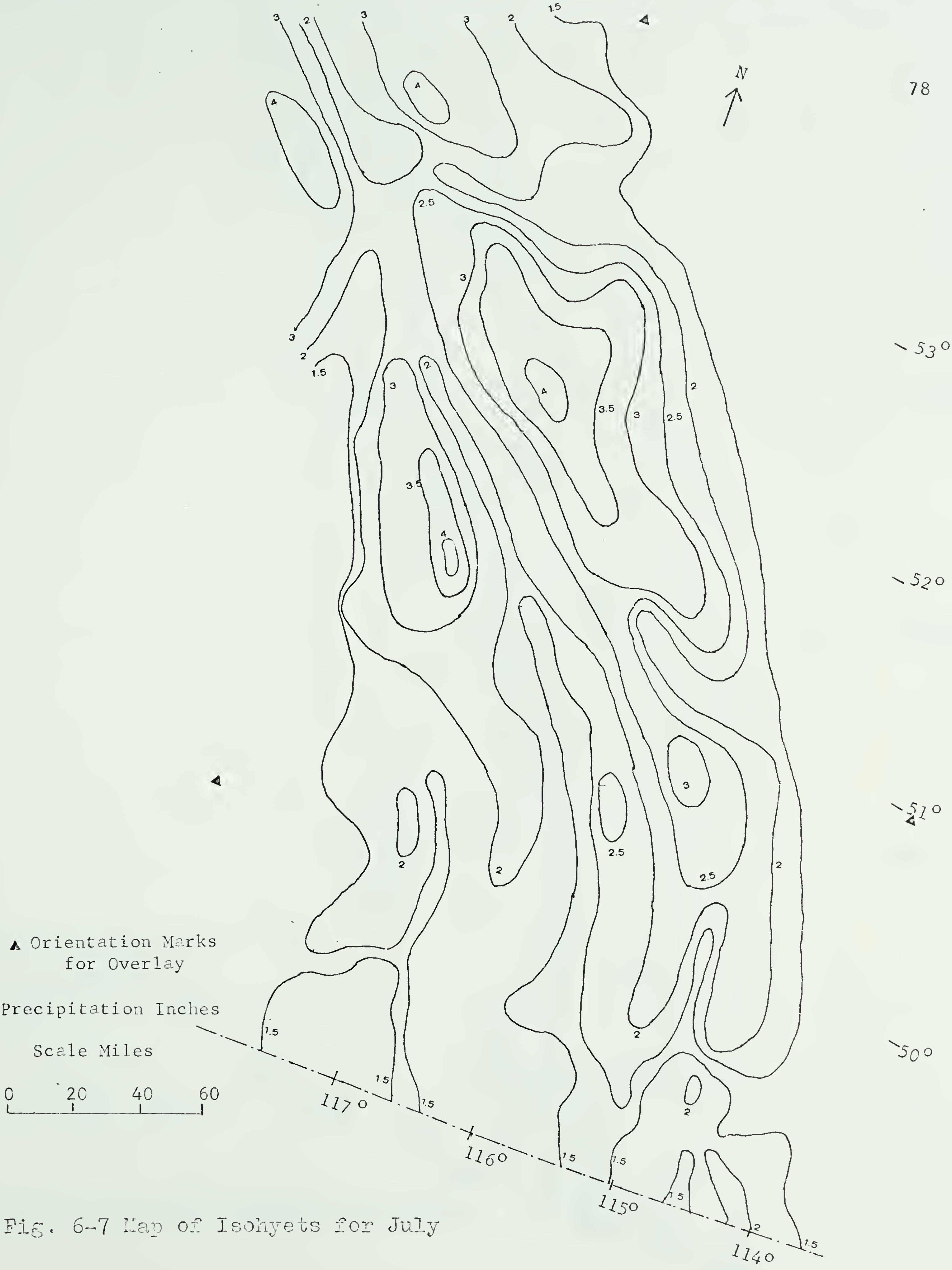


Fig. 6-7 Map of Isohyets for July

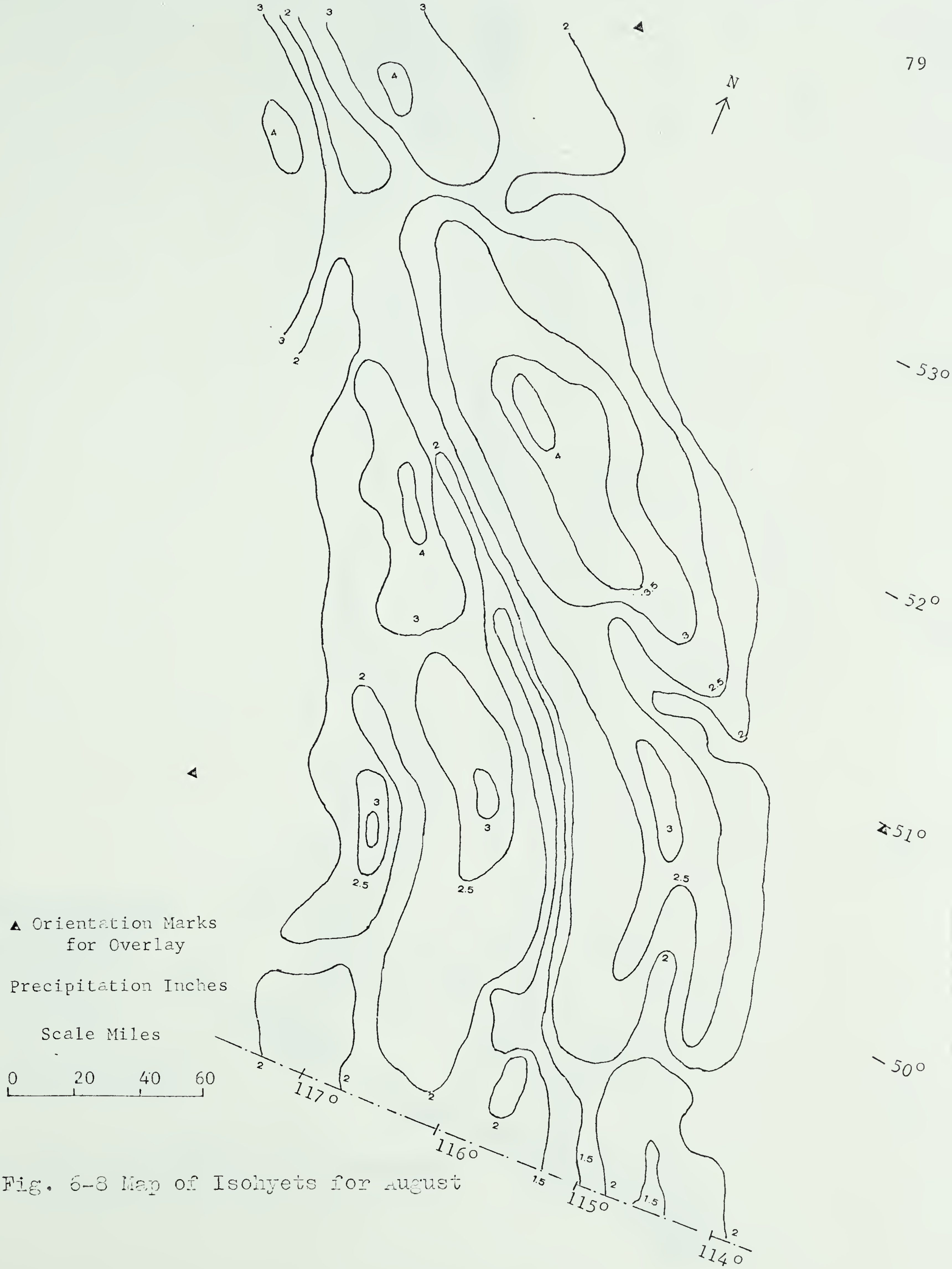


Fig. 6-8 Map of Isohyets for August

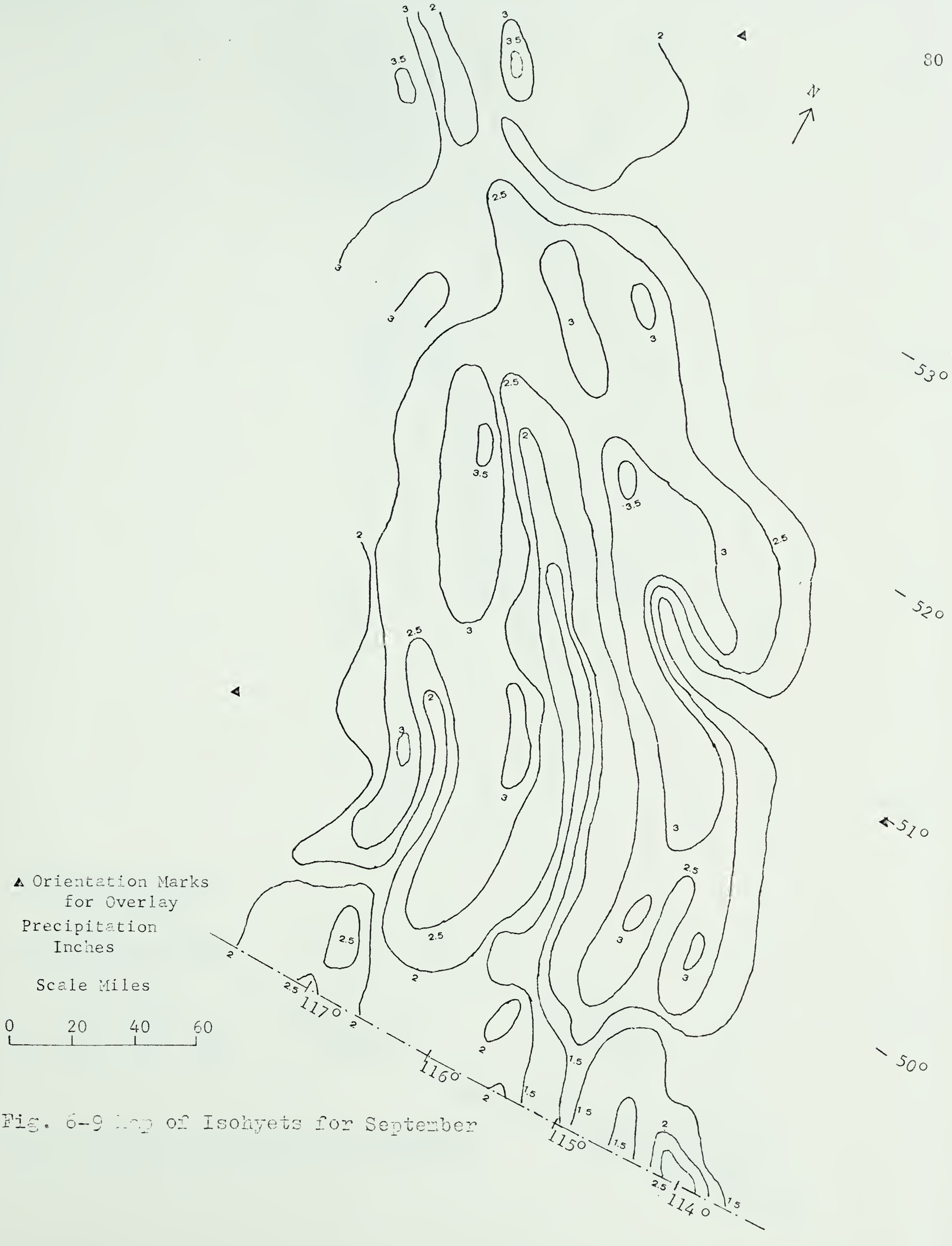


Fig. 6-9 Map of Isohyets for September

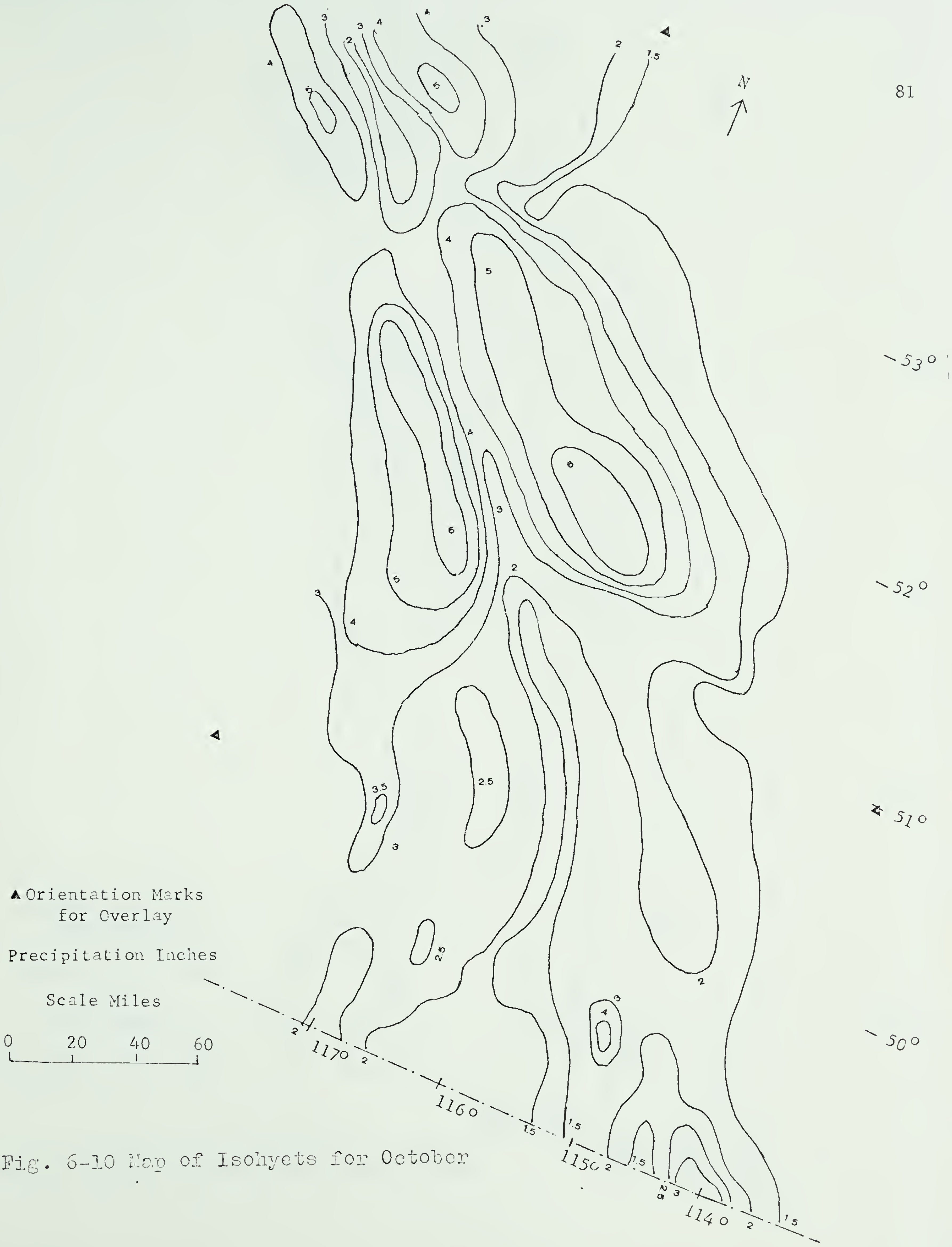


Fig. 6-10 Map of Isohyets for October

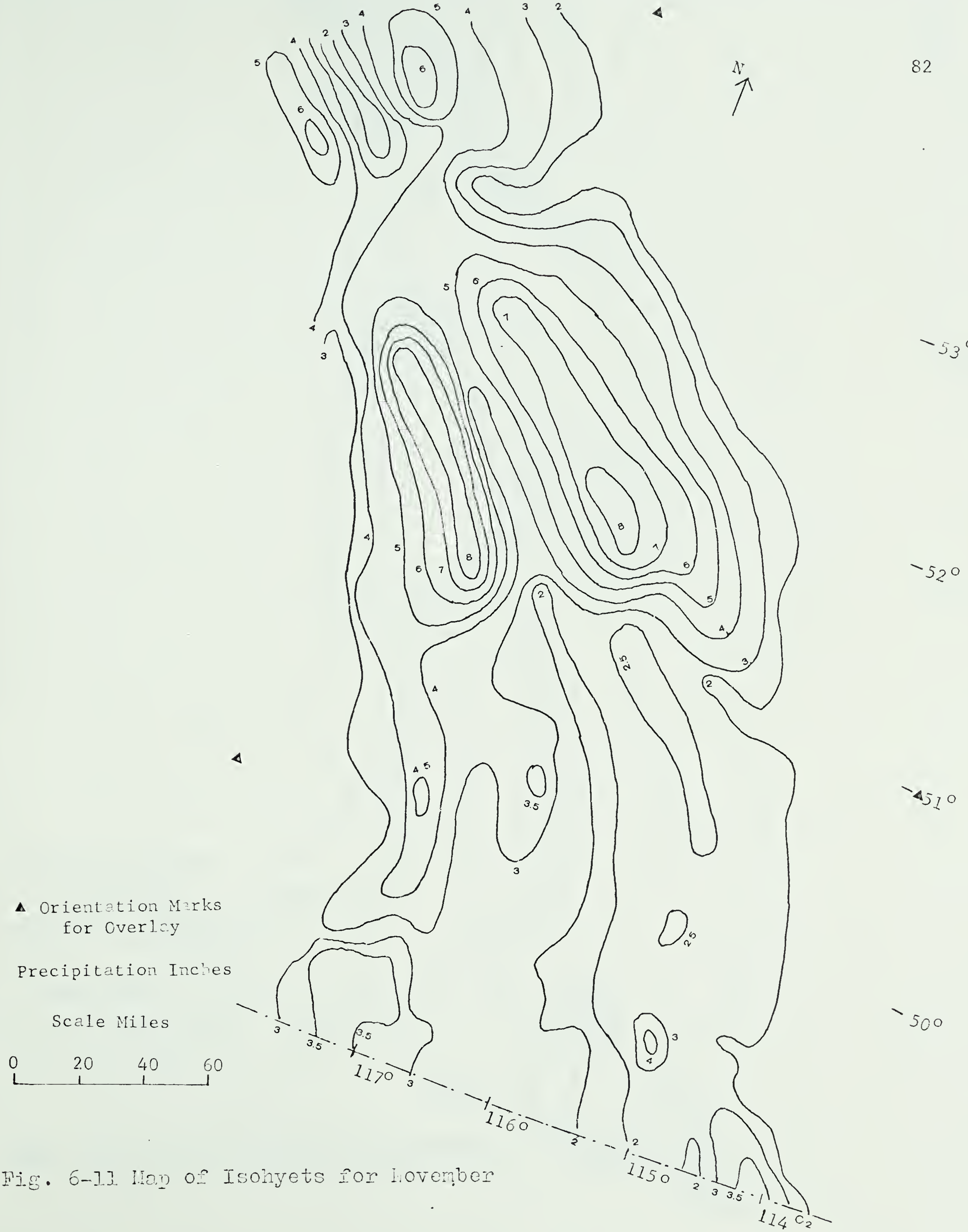
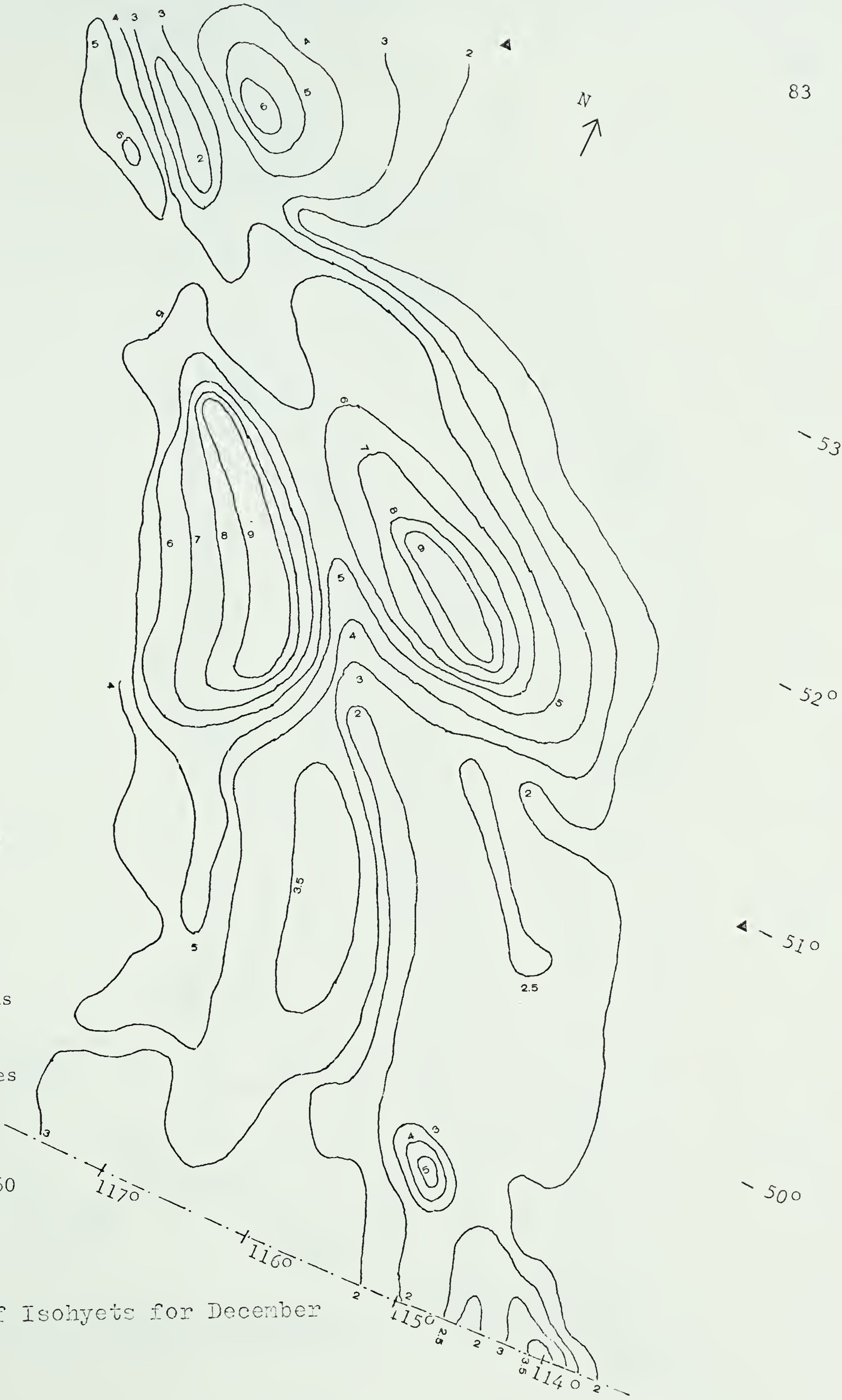


Fig. 6-11 Map of Isohyets for November



▲ Orientation Marks
for Overlay

Precipitation Inches

Scale Miles

0 20 40 60

Fig. 6-12 Map of Isohyets for December

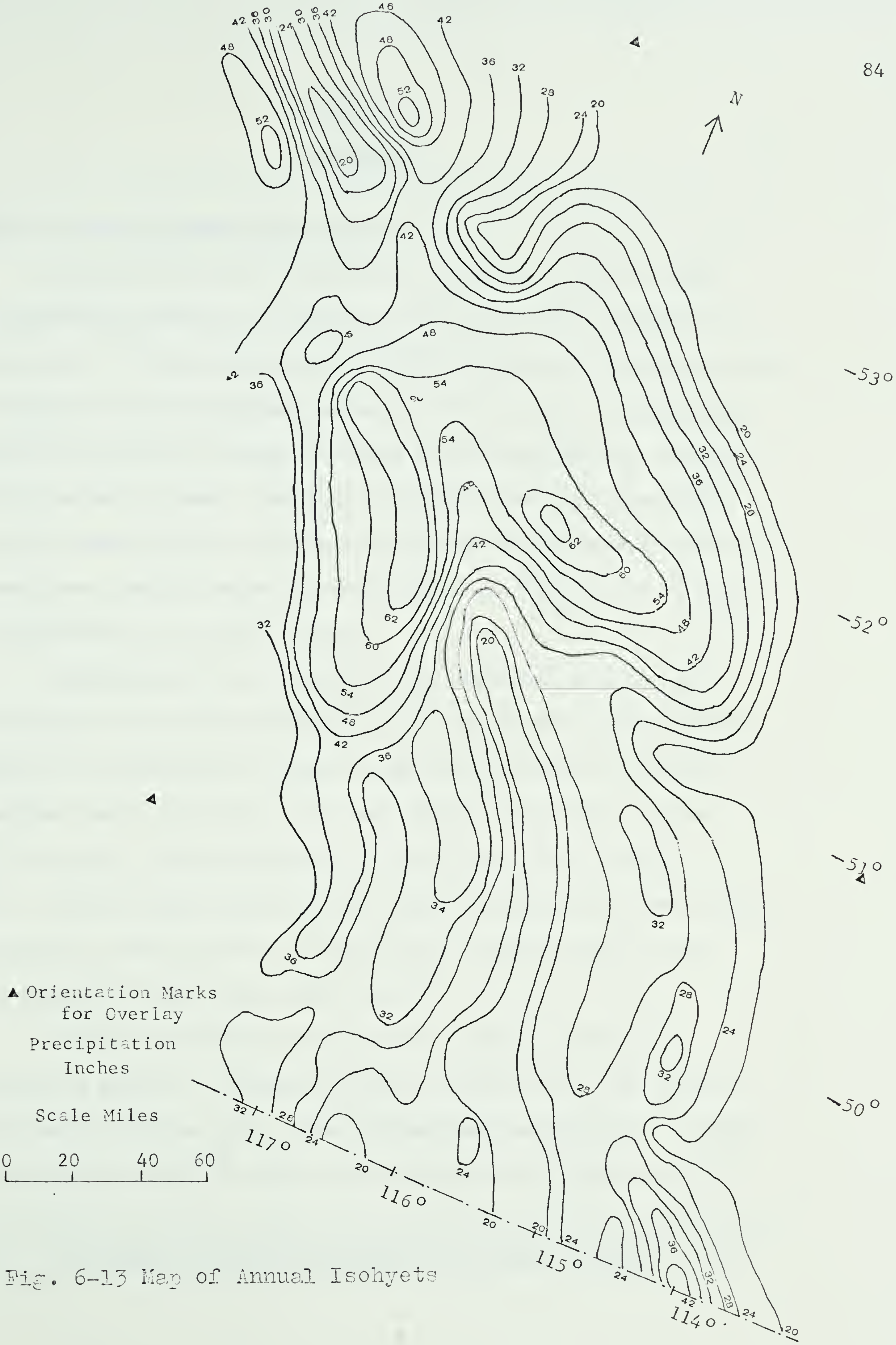


Fig. 6-13 Map of Annual Isohyets

CHAPTER VII

CONCLUSION

Ratio of Snow to Total Precipitation

On the east slope of the Rockies the ratio of snow to total precipitation decreases in general from south to north through the study area. However, there are several exceptions to this general rule. A maximum snow to precipitation ratio of 64% is found at Lake Louise which receives 30.37 inches of annual total precipitation, of which 193.3 inches is snow[1]. Waterton Park HQ,800 feet lower than Lake Louise, and in extreme southwestern Alberta, receives 228.5 inches of snow, more than any other station studied, and 42.31 inches of annual precipitation. Its ratio is 54%.

Taking Glacier as a mid-point, the situation along the western side of the Rockies is reversed. The mean ratio in the northern half of the study area is close to 40%, but only about 33% in the southern half. At Glacier the total annual precipitation averages 57.10 inches, with 370.2 inches of snow giving a ratio of 65%. It is interesting to note that the ratios for Glacier and Lake Louise, situated at about the same latitude but on opposite sides of the Continental Divide, are in effect equal.

If the snow-precipitation ratio of a region is known, it should be possible to deduce the annual precipitation from snowfall estimates, and vice versa. Thus storage gauge measurements of summer precipitation could be used to obtain estimates of snowfall as well.

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[1] 10 inches of snow is equivalent to one inch of water.

It is also conceivable that satellite data of snow cover could be useful for estimating the annual precipitation of remote and inaccessible regions.

Test of the Model

In 1968 the Eastern Rockies Forest Conservation Board published a pamphlet providing precipitation data for the east slopes of the Rockies[2]. These precipitation records, collected by means of storage gauges, are discontinuous and of relatively short duration. Storage rain gauges are known to record less precipitation than standard gauges, the undercatch being as much as 20 percent.

In order to subject the precipitation model developed in Chapter IV to a further test, the precipitation collected at all stations above 7,000 feet was compared with the respective estimated amounts. Table 7-1 summarizes the storage gauge records of the stations used in this comparison.

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[2] Canada, Eastern Rockies Forest Conservation Board, Management Report. No. 2, Alberta, 1968, pp. 4-6.

Table 7-1

Summary of Storage Precipitation Gauge Records

Station	Sugarloaf Summit	Hailstone Butte Lo.	Raspberry Ridge	Forget-me-not	Highwood Summit
Elevation (ft.)	8,250	7,750	7,750	7,600	7,250
Year	Precipitation (inches)				
1953	--	--	--	--	45.5
1954	22.0	--	--	--	41.2
1955	11.1	--	--	--	--
1956	12.6	21.1	17.3	19.1	33.1
1957	11.1	20.0	18.5	16.4	23.4
1958	23.9	30.7	18.5	25.1	32.0
1959	32.3	24.6	16.4	14.9	38.1
1960	27.0	13.3	14.6	13.4	30.1
1961	26.4	22.2	18.8	20.2	42.4
1962	27.8	25.6	12.6	15.5	28.5
1963	--	33.2	16.3	23.7	38.5
1964	--	26.3	20.3	--	43.8
1965	--	25.6	20.9	29.5	41.0
1966	--	23.3	23.7	13.9	30.5
1967	--	18.9	25.3	34.7	37.9
Years of Record	9	12	12	11	14
Highest Year	32.3	33.2	25.3	34.7	45.5
Lowest Year	11.1	13.3	12.6	13.4	23.4

Source: Eastern Rockies Forest Conservation Board.

Table 7-2 gives the estimated values and residuals of the stations listed in Table 7-1

Table 7-2

Summary of Estimated Precipitation and Residuals

Station	Sugarloaf Summit	Hailstone Butte Lo.	Raspberry Ridge	Forget-me-not	Highwood Summit
Average (in.)	21.58	23.73	18.6	20.58	36.14
Estimate (in.)	29.6	29.1	29.1	29.0	28.7
Residual (in.)	8.0	5.4	10.5	8.5	-7.5

Minus sign indicates that the estimated value is less than the actual value.

It is seen from Table 7-1 that the highest measured annual precipitation at Sugarloaf Summit, Hailstone Butte and Forget-me-not exceeds the lowest by a factor of three, and by a factor of two at Raspberry Ridge and Highwood Summit. In order to deal with these wide year to year fluctuations from the true annual but as yet unknown normal, the simple average of the annual precipitation totals was used in the linear relationship $P_H = P_L + C \times DE$. For the east slope in precipitation zone III values of 25.96 inches, 4,380 feet and .94 in./1,000 ft. were used for the annual total precipitation, the elevation and the precipitation index respectively (refer to Table 6-1).

Comparing the actual annual mean precipitation with the estimated amounts listed in Table 7-2, it is seen that the residuals are large. The discrepancies may be attributed to the following:

(1) Storage precipitation gauges which record less precipitation than standard gauges.

(2) The overexposure of high elevation stations may reduce the amount of precipitation recorded.

(3) A single station record does not adequately represent the average precipitation amount for a given elevation level within a large precipitation zone.

The residuals can be reduced by using the grand mean of all five stations. The annual mean precipitation and average elevation of these stations is 24.14 inches and 7,700 feet respectively. At 7,700 feet the estimated precipitation amount is 29.1 inches.

In order to compensate for the undercatch of the storage gauges, it has been found necessary to increase the precipitation catch of such gauges by about 20 percent[3]. When this is done in the present case, the five station average is 28.97 inches, in very good agreement with the estimates for the 7,700 feet level.

A single test of this nature is, of course, far from conclusive, but it is hoped at least that precipitation estimates obtained in this simple manner will be found useful, until more and better measurements have become available.

Suggestion for Further Research

The observing network in the study area is mainly concentrated in the foothills and river basins, and only a few forestry lookout stations are situated at heights above seven thousand feet. Sugarloaf Summit, the highest station, has an altitude of 8,250 feet with nine years of records. In order to obtain a better understanding of precipitation in the mountainous regions of Alberta and British Columbia a much more comprehensive observing network will have to be established on both sides of the Rockies, especially at high elevations.

Reliable upper air data are necessary for input into dynamical models of precipitation forecasting in mountainous areas. The required information may be obtained by setting up rawinsonde stations

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[3] Eastern Rockies Forest Conservation Board, Management Report., op. cit., p. 4.

in pairs, one to sample the air on the windward side, and the other to sample the air on the leeward side of a ridge. Very useful data could be obtained from a rawinsonde pair located in precipitation zone III and IV. Such measurements would form a good physical basis for establishing accurate quantitative relationships between precipitation amounts, air mass characteristics, flow patterns and terrain features[4].

Despite the great complexity of structure and diversity of individual ridges, the Rockies present an almost continuous barrier to the prevailing westerly flow from the Pacific. This feature makes the Rockies an important area for studying the influence of orography on the development and motion of synoptic scale systems, and the effect on storm tracks, frontal structure, and precipitation distribution throughout the year. It is most desirable, therefore, that the network of surface and upper air reporting stations be extended and improved as soon as possible.

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[4] R.D. Elliott and R.W. Shaffer, "The Development of Quantitative Relationships Between Orographic Precipitation and Air-Mass Paremeters for Use in Forecasting and Cloud Seeding Evaluation". J. Appl. Meteor., Vol. 1, 1962, pp. 218-228.

APPENDIX A

Table A-1 Topographic Parameters and Annual Precipitation in Alberta, 1931-60

				Topographic Parameters	
Station Name	Latitude (deg.min.)	Longitude (deg.min)	Precipitation (inches)	Elevation (ft.)	Slope (ft./mi.)
Anthracite	51 12	115 30	18.34	4,550	1,700
Banff	51 11	115 34	18.48	4,583	1,700
Beaver Mines	49 28	114 10	24.36	4,218	400
Caldwell	49 11	113 38	25.59	4,000	100
Carway	49 00	113 22	20.37	4,460	000
Claresholm	49 56	113 45	15.70	3,450	300
Coleman	49 38	114 35	19.91	4,400	500
Cowley	49 41	114 17	19.45	3,920	300
Edson	53 35	116 35	20.85	3,033	000
Entrance	53 22	117 42	19.98	3,300	400
Exshaw	51 04	115 12	20.14	4,260	1,400
Fort MacLeod	49 43	113 24	17.67	3,116	000
High River	50 29	114 10	19.14	3,780	200
Jasper	52 53	118 04	15.98	3,480	1,000
Kananaskis	51 02	115 03	25.09	4,560	1,500
Lake Louise	51 25	116 10	30.37	5,032	1,500
Lyndon	50 01	113 53	20.11	4,100	300
Mountain View	49 08	113 38	22.56	4,325	000
Nordegg	52 28	116 05	21.73	4,300	500
Pekisko	50 22	114 25	25.16	4,721	400
Pincher Creek	49 30	113 57	20.62	3,790	000
Raymond	49 23	112 44	15.98	3,140	000
Rocky Mountain House	52 23	114 55	21.20	3,330	000
Turner Valley	50 43	114 21	22.73	4,000	300
Waterton Lakes Belly R.	49 03	113 42	39.06	4,500	800
Waterton Lakes R Cabin	49 07	113 51	35.76	4,200	900
Waterton Park	49 07	113 44	26.18	4,300	200
Waterton Park HQ	49 03	113 55	42.31	4,200	1,400

Source: Precipitation Normals for Alberta.

Table A-2 Topographic Parameters and Annual Precipitation in British Columbia, 1931-60.

				Topographic Parameters	
Station Name	Latitude (deg.min.)	Longitude (deg.min.)	Precipitation (inches)	Elevation (ft.)	Slope (ft./mi.)
Aberfeldie	49 30	115 21	22.33	2,640	1,400
Barkerville	53 04	131 31	45.25	4,180	500
Blue River	52 09	119 17	40.84	2,243	1,200
Brisco	50 49	116 16	16.39	2,750	1,700
Canal Flats	50 09	115 49	16.15	2,653	1,000
Cranberry Lake Valemount	52 50	119 15	18.47	2,600	1,000
Cranbrook A	49 32	115 46	16.41	3,013	000
Crawford Bay	49 41	116 50	30.94	2,000	1,000
Creston	49 06	116 31	18.94	2,085	1,300
Elko	49 18	115 06	19.70	3.080	1,600
Fernie	49 30	115 03	41.43	3,305	800
Gerrard	50 30	117 18	31.96	2,348	1,400
Glacier	51 14	117 29	57.10	4,094	1,300
Golden	51 18	116 58	18.45	2,583	1,200
Grasmere	49 06	115 05	18.34	2,850	900
Kaslo	49 55	116 55	29.84	1,930	1,400
Kimberley A	49 44	115 47	15.03	3,016	200
Ktny. Radium	50 39	116 01	21.50	3,570	2,700
McBride	53 18	120 10	21.31	2,360	1,300
Mica Creek	52 01	118 34	62.17	1,860	1,700
Nakusp	50 14	117 48	31.34	1,500	1,100
Nelson 2	49 30	117 17	28.62	1,980	900
New Denver	49 59	117 23	28.56	1,850	1,600
Newgate	49 01	115 09	15.03	2,325	600
Red Pass Junction	53 00	119 00	26.74	3,475	1,900
Revelstoke	51 00	118 12	42.54	1,497	2,200
Sinclair Pass	50 40	115 58	22.13	3,840	1,400
Spillimacheen	50 55	116 24	17.31	2,615	900
Wasa	49 49	115 38	14.66	3,050	1,500
Wycliffe	49 35	115 53	17.00	3,000	300
Wynndel	49 11	116 33	23.40	2,025	1,300

Source: Precipitation Normals for British Columbia.

Table A-3 Monthly and Annual Precipitation (inches) in Alberta, 1931-60.

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Anthracite	1.16	1.13	0.91	1.59	1.95	2.68	1.63	2.08	1.55	1.27	1.18	1.21	19.34
Banff	1.29	1.18	0.97	1.38	1.77	2.45	1.67	1.97	1.39	1.57	1.32	1.52	18.48
Beaver Mines	1.85	1.67	1.93	2.15	2.44	3.70	1.41	1.86	2.07	1.82	1.70	1.76	24.36
Caldwell	1.94	1.66	1.80	2.56	2.90	4.21	1.56	1.70	1.98	1.93	1.69	1.66	25.59
Carway	1.12	1.34	1.52	1.80	2.42	3.61	1.56	1.51	1.77	1.41	1.15	1.16	20.37
Claresholm	0.76	1.04	1.29	1.35	1.73	2.65	1.29	1.60	1.31	0.95	0.93	0.80	15.70
Coleman	1.52	1.40	1.26	1.56	2.02	2.53	1.25	1.64	1.65	1.64	1.72	1.72	19.91
Cowley	1.24	1.11	1.51	1.42	2.07	3.10	1.49	1.30	1.68	1.43	1.49	1.61	19.45
Edson	1.00	0.75	0.95	1.06	2.05	3.59	3.66	3.16	1.63	0.98	1.03	0.99	20.85
Entrance	0.81	0.73	0.97	1.22	2.10	3.59	2.72	3.10	1.81	1.11	0.95	0.87	19.98
Exshaw	0.81	0.67	1.58	1.63	2.54	3.41	2.02	1.97	2.05	1.49	1.06	0.91	20.14
Fort MacLeod	0.73	0.95	1.16	1.28	2.39	3.60	1.67	1.57	1.70	0.94	0.93	0.75	17.67
High River	0.76	1.00	1.16	1.77	2.17	3.57	2.08	2.20	1.63	1.13	0.85	0.82	19.14
Jasper	1.10	0.99	0.63	0.73	1.31	2.15	1.96	2.01	1.42	1.15	1.24	1.29	15.98
Kananaskis	1.04	1.47	1.53	2.28	3.15	4.36	2.57	2.86	2.09	1.46	1.18	1.10	25.09
Lake Louise	3.09	2.54	2.08	2.08	1.93	2.46	1.96	2.28	1.96	2.61	3.24	4.14	30.37
Lyndon	0.73	1.16	1.38	1.76	2.47	3.90	1.94	1.94	1.72	1.21	1.00	0.90	20.11
Mountain View	1.31	1.53	1.66	2.29	2.83	3.71	1.43	1.55	1.85	1.56	1.39	1.45	22.56
Nordegg	1.02	0.96	1.27	1.34	2.42	4.18	3.17	3.00	1.60	1.01	0.96	0.80	21.73
Pekisko	1.08	1.51	1.72	2.33	2.97	4.53	2.09	2.63	2.24	1.53	1.21	1.32	25.16
Pincher Creek	1.12	1.19	1.41	1.75	2.55	3.77	1.50	1.79	1.92	1.34	1.24	1.04	20.62
Raymond	0.82	0.81	1.06	1.68	1.66	2.45	1.21	1.69	1.28	1.15	1.22	0.95	15.98
Rocky Mtn. House	0.87	0.93	1.06	1.48	2.23	3.69	3.32	2.97	1.94	0.98	0.78	0.95	21.20
Turner Valley	0.77	1.18	0.99	2.59	2.42	4.22	2.90	3.40	1.51	1.04	0.78	0.93	22.73
Waterton L. Belly R.	2.85	3.19	3.34	4.15	3.98	5.52	2.03	2.35	3.02	2.42	3.24	2.97	39.06
Waterton LR Cabin	3.30	2.95	2.40	3.71	3.68	4.90	1.85	1.96	2.71	2.69	2.91	2.70	35.76
Waterton Park	1.94	1.89	1.95	2.61	2.79	3.72	1.33	1.45	2.31	2.15	1.86	2.18	26.18
Waterton Park HQ	4.44	4.11	3.68	4.43	3.54	5.17	1.88	1.96	2.83	3.27	3.52	3.48	42.31

Source: Precipitation Normals for Alberta.

Table A-4 Monthly and Annual Precipitation (inches) in British Columbia, 1931-60.

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Aberfeldie	3.30	1.85	1.04	1.02	1.80	2.91	1.01	1.66	1.61	1.65	2.21	2.27	22.33
Barkerville	4.58	3.68	4.14	2.42	2.56	4.36	3.78	4.27	3.33	3.57	4.31	4.25	45.25
Blue River	4.28	3.28	2.80	2.11	2.54	3.26	3.18	3.23	2.88	3.89	4.41	4.98	40.84
Brisco	1.68	1.04	0.72	0.97	1.43	2.13	1.20	1.41	1.17	1.40	1.35	1.89	16.39
Canal Flats	1.25	1.36	0.93	0.90	1.69	2.22	0.95	1.34	1.13	1.34	1.41	1.63	16.15
Cranberry Lake Valemount	1.33	1.22	0.96	0.95	1.32	1.85	1.85	1.65	1.71	1.93	1.87	1.83	18.47
Cranbrook A	1.77	1.53	0.85	0.85	1.46	2.22	0.91	1.24	1.06	1.36	1.39	1.77	16.41
Crawford Bay	4.10	2.92	2.57	1.69	2.05	2.17	1.20	1.86	2.08	2.39	3.80	4.11	30.94
Creston	2.44	1.66	1.35	0.99	1.19	1.89	0.75	1.01	1.12	1.78	2.21	2.55	18.94
Elko	2.07	1.35	1.07	1.13	1.70	2.56	1.08	1.42	1.41	2.01	1.97	1.93	19.70
Fernie	5.54	4.23	3.35	2.62	2.32	3.05	1.49	1.72	2.36	4.55	4.24	5.96	41.43
Gerrard	5.03	3.25	2.09	1.48	1.50	2.19	1.63	0.98	1.67	2.93	4.21	5.00	31.96
Glacier	7.73	6.07	4.99	3.07	2.56	3.27	2.87	2.78	3.74	5.03	6.66	8.33	57.10
Golden	2.24	1.57	0.85	0.97	1.13	1.54	1.24	1.38	1.30	1.61	1.94	2.68	18.45
Grasmere	1.53	0.73	0.89	1.57	1.78	3.27	1.23	2.00	1.38	0.82	1.46	1.68	18.34
Kaslo	4.00	3.11	2.15	1.49	1.68	2.20	1.37	1.56	1.66	2.86	3.25	4.51	29.84
Kimberley A	1.78	1.23	0.83	0.75	1.27	1.97	0.73	1.36	0.90	1.21	1.36	1.64	15.03
Ktny. Radium	1.57	1.09	0.85	1.54	1.80	3.07	2.54	1.93	2.22	1.45	1.36	2.08	21.50
McBride	2.10	1.63	1.62	1.20	1.20	1.68	1.78	1.88	1.80	2.10	2.10	2.22	21.31
Mica Creek	9.95	5.98	4.86	3.58	2.29	2.54	3.07	3.28	2.72	6.33	8.33	9.24	62.17
Nakusp	3.65	2.58	2.00	1.44	2.63	2.84	1.94	1.29	2.38	3.01	2.92	4.66	31.34
Nelson 2	3.76	2.69	2.03	1.57	2.02	2.69	1.23	1.35	1.69	2.88	2.81	3.90	28.62
New Denver	3.59	2.61	2.20	1.54	2.07	2.47	1.33	1.50	1.76	2.90	2.71	3.88	28.56
Newgate	1.85	1.18	1.05	0.79	1.32	1.72	0.75	0.92	0.94	1.20	1.50	1.81	15.03
Red Pass Junction	3.08	2.08	2.11	1.23	1.26	1.89	1.96	2.23	1.80	2.34	3.16	3.60	26.74
Revelstoke	6.26	4.49	3.01	2.12	1.83	2.97	2.00	1.94	2.81	4.05	4.62	6.44	42.54
Sinclair Pass	1.68	1.64	1.38	1.37	2.45	3.01	1.94	2.00	1.59	1.84	1.22	2.01	22.13
Spillimacheen	1.78	0.93	0.36	1.03	1.69	2.01	1.73	1.45	1.38	1.12	1.92	1.91	17.31
Wasa	1.38	1.03	0.87	0.84	1.45	1.97	0.92	1.14	1.07	1.39	1.13	1.47	14.66
Wycliffe	1.99	1.39	0.80	0.98	1.88	1.87	0.84	1.15	1.27	0.75	2.09	1.99	17.00
Wynndel	2.16	2.06	1.86	1.04	2.02	1.72	1.03	1.46	1.16	2.23	3.24	3.42	23.40

Source: Precipitation Normals for British Columbia.

APPENDIX B

Table B-1

Summary of Old Glory Mountain Region

Slope Direction	Average Elevation (Thousands of ft.)	Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
West	1.9	Average Precip. (in.)	1.83	1.35	1.16	1.01	1.68	2.22	0.91	1.00	1.10	1.65	1.52	1.87
		Index C (in./1,000 ft.)	0.20	0.24	0.29	0.17	0.08	0.16	0.11	0.16	0.16	0.11	0.22	0.20
East	1.6	Average Precip. (in.)	3.12	2.27	2.12	1.48	1.98	2.26	1.08	1.21	1.51	2.19	3.03	3.46
		Index C (in./1,000 ft.)	$\bar{0}.02$	0.08	0.12	0.09	0.03	0.14	0.07	0.12	0.09	0.02	$\bar{0}.04$	$\bar{0}.07$

Stations on the west slope: Greenwood, Grand Forks, Deer Park.

Stations on the east slope: Castlegar, Columbia Gardens, Robson, Trail, Waneta.

Table B-2

Summary of Fictitious Station Region

Slope Direction	Average Elevation (Thousands of ft.)	Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
West	9.7	Average Precip. (in.)	8.8	6.0	4.9	3.3	2.4	2.9	3.0	3.0	3.2	5.7	7.5	8.8
		Index C (in./1,000 ft.)	0.31	0.19	0.23	0.14	0.07	-0.07	0.12	0.13	0.05	0.20	0.35	0.29
East		Index C (in./1,000 ft.)	1.06	0.65	0.54	0.23	0.01	0.08	0.20	0.15	0.23	0.58	0.81	0.88

Table B-3

Summary of Stations in Each Precipitation Zone

Precip. Zone	Slope Direction	Average Elevation (Thousands of ft.)	Average Precipitation (in.) Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
I	west	1.62	3.25	2.35	2.11	1.48	2.07	2.36	1.22	1.26	1.65	2.38	2.98	3.66
	east	2.01	3.18	2.44	1.98	1.30	1.74	2.00	1.09	1.47	1.51	2.32	3.13	3.65
II	west	2.01	3.18	2.44	1.98	1.30	1.74	2.00	1.09	1.47	1.51	2.32	3.13	3.65
	east	2.86	1.71	1.19	0.82	1.02	1.54	2.18	1.19	1.39	1.26	1.24	1.54	1.87
III	west	2.86	1.71	1.19	0.82	1.02	1.54	2.18	1.19	1.39	1.26	1.24	1.54	1.87
	east	4.38	1.79	1.84	1.87	2.45	2.78	3.89	1.78	2.02	2.11	1.85	1.79	1.79
IV	west	1.50	6.26	4.49	3.01	2.12	1.83	2.97	2.00	1.94	2.81	4.05	4.62	6.44
	east	5.03	3.09	2.54	2.08	2.08	1.93	2.46	1.96	2.28	1.96	2.61	3.24	4.14
V	west	2.67	2.70	2.05	1.87	1.37	1.58	2.17	2.19	2.25	2.05	2.57	2.89	3.16
	east	3.69	0.98	0.89	0.96	1.10	1.94	3.31	2.62	2.70	1.61	1.09	1.05	0.99

Refer to Table 4-1

Table B-4

Estimated Precipitation on the Mountain Tops

Precip. Zone	Average Elev. of Peaks (Thousands of ft.)	Slope Direction	Estimated Precipitation (in.)											
			Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
I	10.1	west	5.0	4.4	4.6	2.9	2.8	3.7	2.2	2.6	3.0	3.3	4.8	5.4
		east	3.0	3.1	3.0	2.0	2.0	3.1	1.7	2.5	2.2	2.5	2.8	3.1
II	10.6	west	4.2	4.1	4.0	2.5	2.2	3.2	1.9	2.8	2.6	3.0	4.3	4.6
		east	2.8	2.7	2.8	2.3	2.2	3.7	2.0	2.4	2.4	1.9	2.5	2.8
III	10.7	west	1.7	1.7	1.8	2.0	2.0	3.6	2.0	2.3	2.1	1.2	1.5	1.6
		east	3.0	3.4	3.7	3.5	3.4	5.0	2.4	2.9	3.1	2.7	3.0	2.9
IV	10.7	west	9.1	6.2	5.1	3.4	2.5	2.9	3.1	3.1	3.3	5.9	7.8	9.1
V	11.1	west	5.3	3.6	3.8	2.6	2.2	2.1	3.2	3.3	2.5	4.2	5.8	5.6
		east	8.9	5.7	5.0	2.7	2.0	3.9	4.1	3.8	3.3	5.4	7.0	7.5

Table B-5

Weighted Mean Precipitation on the Mountain Tops

Precip. Zone	Ave. Elevation of Peaks (Thousands of ft.)	Weighting Factor		Weighted Mean Precipitation (in.)											
		West	East	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
I	10.1	2/3	1/3	4.3	4.0	4.0	2.6	2.5	3.5	2.0	2.6	2.8	3.0	4.2	4.6
II	10.6	4/15	11/15	3.2	3.0	3.1	2.3	2.2	3.5	2.0	2.5	2.5	2.2	3.0	3.3
III	10.7	11/24	13/24	2.4	2.6	2.9	2.8	2.7	4.3	2.2	2.6	2.7	2.0	2.3	2.3
IV	10.7	1/2	1/2	9.1	6.2	5.1	3.4	2.5	2.9	3.1	3.1	3.3	5.9	7.8	9.1
V	11.1	4/7	3/7	6.8	4.5	4.3	2.6	2.1	2.9	3.6	3.5	2.8	4.7	6.4	6.4

Table B-6

Precipitation Indices C

Precip. Zone	Average Elev. of Peaks (Thousands of ft.)	Slope Direction	Precipitation Index C (in./1,000 ft.)											
			Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
I	10.1	west	0.12	0.19	0.23	0.14	0.05	0.14	0.09	0.15	0.13	0.08	0.14	0.11
		east	0.14	0.19	0.25	0.16	0.09	0.19	0.11	0.13	0.15	0.09	0.13	0.12
II	10.6	west	0.0	0.07	0.13	0.12	0.06	0.18	0.10	0.12	0.11	$\bar{0}.01$	$\bar{0}.01$	$\bar{0}.04$
		east	0.19	0.24	0.29	0.17	0.09	0.17	0.10	0.14	0.16	0.13	0.19	0.18
III	10.7	west	0.10	0.18	0.26	0.23	0.15	0.27	0.13	0.16	0.18	0.09	0.10	0.05
		east	0.10	0.12	0.15	0.06	0.06	0.07	0.07	0.10	0.09	0.02	0.08	0.08
IV	10.7	west	0.31	0.19	0.23	0.14	0.07	0.0	0.12	0.13	0.05	0.20	0.35	0.29
		east	1.06	0.65	0.54	0.23	0.01	0.08	0.20	0.15	0.23	0.58	0.81	0.88
V	11.1	west	0.49	0.29	0.29	0.15	0.06	0.08	0.17	0.15	0.09	0.26	0.41	0.39
		east	0.79	0.49	0.45	0.22	0.02	$\bar{0}.06$	0.13	0.11	0.16	0.49	0.72	0.73

Table B-7

Estimated Precipitation and Residual at 7,700 feet (Old Glory Mtn. Ht.)

Precip. Zone	Slope Direction	Precipitation (in.)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
I	west	Estimate	4.0	3.5	3.5	2.3	2.3	3.2	1.8	2.2	2.4	2.8	2.8	4.3
		Residual	1.0	0.8	0.7	0.3	0.2	0.0	0.2	0.2	0.4	0.6	0.0	1.3
	east	Estimate	4.0	3.5	3.4	2.2	2.3	3.1	1.7	2.2	2.4	2.8	3.9	4.3
		Residual	1.0	0.8	0.6	0.2	0.1	0.0	0.2	0.3	0.3	0.5	1.1	1.3
II	west	Estimate	3.2	2.8	2.7	2.0	2.1	3.0	1.7	2.2	2.1	2.4	3.1	3.4
		Residual	0.2	0.1	$\bar{0}.1$	0.0	0.0	$\bar{0}.1$	0.1	0.2	0.1	0.1	0.3	0.4
	east	Estimate	2.6	2.4	2.2	1.8	2.0	3.0	1.7	2.1	2.0	1.9	2.5	2.7
		Residual	$\bar{0}.4$	$\bar{0}.4$	$\bar{0}.6$	$\bar{0}.2$	$\bar{0}.2$	$\bar{0}.1$	0.1	0.1	0.0	$\bar{0}.4$	$\bar{0}.4$	$\bar{0}.2$
III	west	Estimate	2.2	2.1	2.1	2.1	2.3	3.5	1.8	2.2	2.1	1.7	2.0	2.1
		Residual	$\bar{0}.8$	$\bar{0}.6$	$\bar{0}.8$	0.1	0.1	0.4	0.3	0.2	0.1	$\bar{0}.6$	$\bar{0}.8$	$\bar{0}.9$
	east	Estimate	2.1	2.2	2.8	2.7	2.8	4.1	2.0	2.4	2.4	1.9	2.1	2.1
		Residual	$\bar{0}.9$	$\bar{0}.5$	$\bar{0}.5$	0.6	0.6	1.0	0.5	0.4	0.4	$\bar{0}.4$	$\bar{0}.7$	$\bar{0}.9$

Table B-8

Elevation and Monthly Precipitation (inches) in Old Glory Mountain Region, 1931-1960.

Station	Elevation(ft.)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Deer Park	1,460	1.80	1.33	1.18	0.98	1.57	2.13	1.03	1.11	1.22	1.87	1.50	1.98
Grand Forks	1,746	1.94	1.42	1.14	0.96	1.54	2.03	0.74	0.94	1.04	1.68	1.61	2.09
Greenwood	2,490	1.76	1.30	1.16	1.10	1.94	2.50	0.97	0.96	1.03	1.40	1.46	1.54
Old Glory Mt.	7,700	3.00	2.73	2.85	2.01	2.15	3.13	1.54	1.95	2.03	2.31	2.81	3.01
Waneta	1,880	2.97	2.12	1.92	1.39	2.01	2.39	1.23	0.99	1.34	2.30	2.33	3.03
Columbia Gardens	1,420	3.05	2.20	1.90	1.44	2.00	2.46	1.07	1.07	1.41	2.32	2.71	3.27
Trail(Warfield)	1,987	3.52	2.69	2.21	1.63	1.83	2.52	1.14	0.92	1.44	2.58	2.81	3.62
Castlegar	1,425	2.76	2.23	2.10	1.43	1.87	1.88	0.77	1.32	2.03	2.16	2.99	3.29
Robson	1,450	3.55	2.26	2.30	1.57	1.84	2.52	1.34	1.40	1.49	2.31	3.12	3.60

Source: Precipitation Normals for British Columbia.

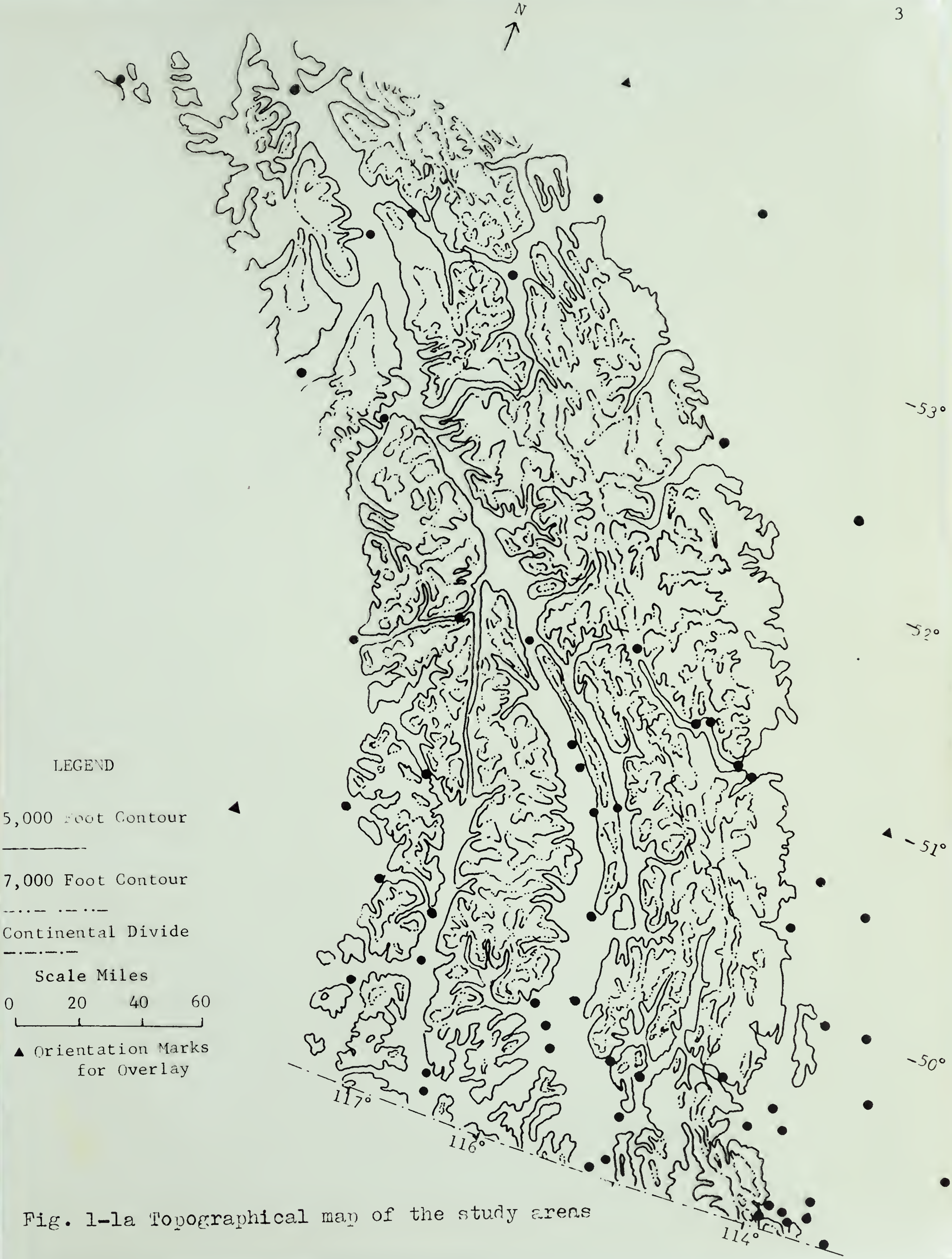

Fig. 1-1a Topographical map of the study areas

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